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FINAL REPORT

ULTRASONIC SEAM WELDING ON THIN SILICON SOLAR CELLS

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TECHNICAL CONTENT

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The author thanks the Hughes personnel who have contributed to this project. Pilar McAdam made all photovoltaic measurements and did much of the matrix series of welds. Mr. E.R. Browne, Jr., was the engineer directing the modifications of the welding machine. His experience and insight into the ultrasonic welding process were invaluable to the success of this project.

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1. ABSTRACT

The ultrathin silicon solar cell has progressed to where it is a serious candidate for future light weight or radiation tolerant spacecraft. This report describes progress at the Hughes Aircraft Company in using an ultrasonic seam welder to bond interconnects to these cells. This work is one of three concurrent cell welding projects under sponsorship of NASA/JPL.

The ultrasonic method of producing welds was found to be satisfactory. These ultrathin cells could be handled without breakage in a semi-automated welding machine. This is a prototype of a machine capable of production rates sufficiently large to support spacecraft array assembly needs. For comparative purposes, this project also welded a variety of cells with thicknesses up to 0.23 mm as well as the 0.07 mm ultrathin cells.

There was no electrical degradation in any cells. The mechanical pull strength of welds on the thick cells was excellent when using a large welding force. The mechanical strength of welds on thin cells was less since only a small welding force could be used without cracking these cells. Even so, the strength of welds on thin cells appears adequate for array application. The ability of such welds to survive multiyear, near Earth orbit thermal cycles needs to be demonstrated.

2. INTRODUCTION

Ultrathin silicon solar cells have been in development by NASA-OAST during the past few years as part of a program to meet future requirements for large area, very light weight solar arrays for space operation. This development has been directed by the Jet Propulsion Laboratory (JPL) of the California Institute of Technology, under Contract Number NAS7-100, sponsored by the National Aeronautics and Space Administration. A few thousand of these ultrathin (0.05 to 0.10 mm) cells have been fabricated by three solar cell manufactures on pilot plant lines to demonstrate the feasibility of making these cells in large scale production. Demonstration of methods for electrically interconnecting these cells into viable solar array assemblies now is in progress. The work described in this report is part of this demonstration, having been performed by Hughes Aircraft Company (Hughes) under sponsorship by JPL to assess the feasibility of using ultrasonic welding to make these interconnections.

Welding of solar cell interconnects has received increasing attention during the past few years. Welding has purported advantages over soldering for arrays where weight saving is critical or for arrays subjected to unusual temperature extremes. Several European constructed solar arrays have used welding. The Helios mission for exploring the Sun, the Canadian Technology Satellite, the Space Telescope and Intelsat V are examples of important spacecraft use of welded solar cell interconnects. Major solar array fabricators in the United States, on the other hand, have continued using soldering to attach interconnects. Soldering is a reliable, established process that has served well for past arrays. However, with increasing power and lifetime requirements, welding can be advantagous. Several U.S. solar array manufactures, including Hughes, are now investigating welded interconnects. The feasibility of welding for silicon solar cells of conventional thicknesses has been established. The feasibility of welding to ultrathin cells has yet to be placed on a solid footing. Welding processes need to be optimized to produce bonds of adequate electrical and mechanical integrity without damaging the fragile cells.

The limits of weld parameters useful for producing acceptable welds need to be defined so that in the future appropriate quality assurance steps can be defined.

During the past 10 years, Hughes has experimented with three methods of welding interconnects: parallel gap, ultrasonic, and laser welding. Of these, ultrasonic welding has appeared to hold the best promise of a rapid technique that is relatively insensitive to the variables that might reasonably be expected to occur when working with the large number of cells and interconnects required for large spacecraft. Several thousand solar cells have now been welded at Hughes on an assembly machine that is a development model for a production machine. Figure 2.0-1 shows an example of a solar panel having welded solar cell interconnects assembled on this welding machine.

Figure 2.0-1 An Example of a Welded Solar Panel.

3. TECHNICAL DISCUSSION

3.1 REQUIREMENTS

The objective of this program has been to demonstrate a consistent, controlled and reliable method of welding interconnects to ultrathin (0.07 mm thick) silicon solar cells. This welding must satisfy the quality and reliability requirements associated with space flight hardware and be adaptable to processing the large number of cells required for future spacecraft.

All welds have been made using the Hughes Ultrasonic Seam Welding Machine. This machine had been used on a previous technology program to weld successfully 7000 silicon solar cells that were 0.25 mm thick. The machine controls not only the welding conditions but also the precision of placement of the interconnects on the cells. The use of this machine has been a major factor in conducting the present program. Starting with cells 0.20 mm thick, then progressing to thinner and thinner cells, the machine was modified as required to obtain mechanically and electrically effective welds of the interconnects to the ultrathin cells. Machine characteristics investigated included: supporting pad rigidity, power settings, contact time, weld head force, and configuration of cell clamping mechanism. In anticipation of future application of this welding to production quantities of ultrathin cells, investigation was made of the tolerence that must be maintained on the many weld parameters in order to achieve an acceptably reproducible weld strength. Evaluation of the success of the welds was made by optical examination, by mechanical pull tests, by thermal cycling, and by photovoltaic measurement.

3.2 SOLAR CELL WELDING MACHINE

Over the past several years Hughes has been investigating welding of interconnects to solar cells. As work has progressed, the focus has been placed on ultrasonic welding. Seam welding has been chosen as a simple means of welding to a large number of cells. To investigate the suitability of adapting seam ultrasonic welding to future mass production, a prototype welding machine has been constructed. This machine controls the principal welding parameters of weld tip contact force, of dwell time on the work piece, and of the ultrasonic power applied to the weld tip. It also controls the dimenisonal precision of placing interconnects on the front and on the back of solar cells, and the resultant cell to cell spacing. Several thousand solar cells of 0.25 mm thickness previously have been welded satisfactorily on this prototype machine. With its present manually operated control console this machine can weld up to 200 2x6 cm (or 600 2x2 cm) cells a day. A microprocessor control unit soon will be substituted for the manually operated console, and the production rate is expected to increase to at least 800 2x6 cm cells per day.

The prototype machine is representative of a practical production configuration. It has been used extensively on a previous program where it demonstrated satisfactory welding on silicon solar cells of conventional thickness. Thus, this prototype welder has been a good test bed for investigating the feasibility of welding ultrathin solar cells at acceptable production rates. The principle weld parameters can be varied at will over a wide range and then be set and maintained with precision to any specific value within this range. Furthermore, the various cell transfer mechanisms and cell alignment surfaces are similar to those that would exist on a production machine. The use of these mechanisms on the ultrathin solar cells provides meaningful experience for predicting handling problems that might arise in future production situations. A significant part of the present investigation therefore has been directed toward determining those modifications required to the prototype machine to permit it to weld the ultrathin cells without damage during welding or during transfer operation. For this reason the prototype machine is described here in detail.

The heart of this welding machine is a rotating, wheel-shaped welding tip. This wheel is rotated along the interconnect and solar cell as indicated schematically in Figure 3.2-1. The resultant weld between the interconnect and solar cell thus is a continuous seam across the full width of the solar cell. Thr rotational rate and translation speed of the wheel are controlled so the wheel is in rolling contact with the interconnect. There is no sliding motion between the wheel and interconnect in the direction of wheel translation. Ultrasonic energy is generated at the power supply and converted to a mechanical resonance by a transducer brazed to the end of the weld horn. This weld horn amplifies and transmits this vibration to the center of the weld wheel. The welding wheel then resonantes at the input frequency (50,000 H_z). The welding wheel transmits this energy into the interconnect and cell surface, resulting in a weld junction. The entire transducer, horn, and wheel rotate within a bearing housing to produce the rolling motion of the weld wheel. During welding the cell is supported on a rigid steel anvil. Small vacuum ports exist in this anvil under the solar cell so that the cell is held in place by the atmospheric pressure differential across the cell. The correct alignment of the cell with respect to the path of the weld wheel is maintained by a horizontal clamp which presses on one edge of the cell, forcing the opposite edge of the cell against a fixed alignment step on the anvil. The alignment of the interconnect is maintained by holding the interconnect firmly along its outer edge with a pair of clamping jaws. A photograph of a welding station is shown in Figure 3.2-2.

The weld parameters of contact force, wheel speed, and ultrasonic energy were varied systematically during this program to determine an optimum set of conditions. The optimum conditions were found to lie well within the large range of power, force, and speed that can be achieved on this machine. Within this range any value can be selected and maintained with precision from one weld to the next. The weld clamping force (the force pressing the wheel against the interconnect during welding) can be varied over the range from 1 to 10 newtons. The wheel translation velocity is variable from 0.3 to 1.5 cm/sec.

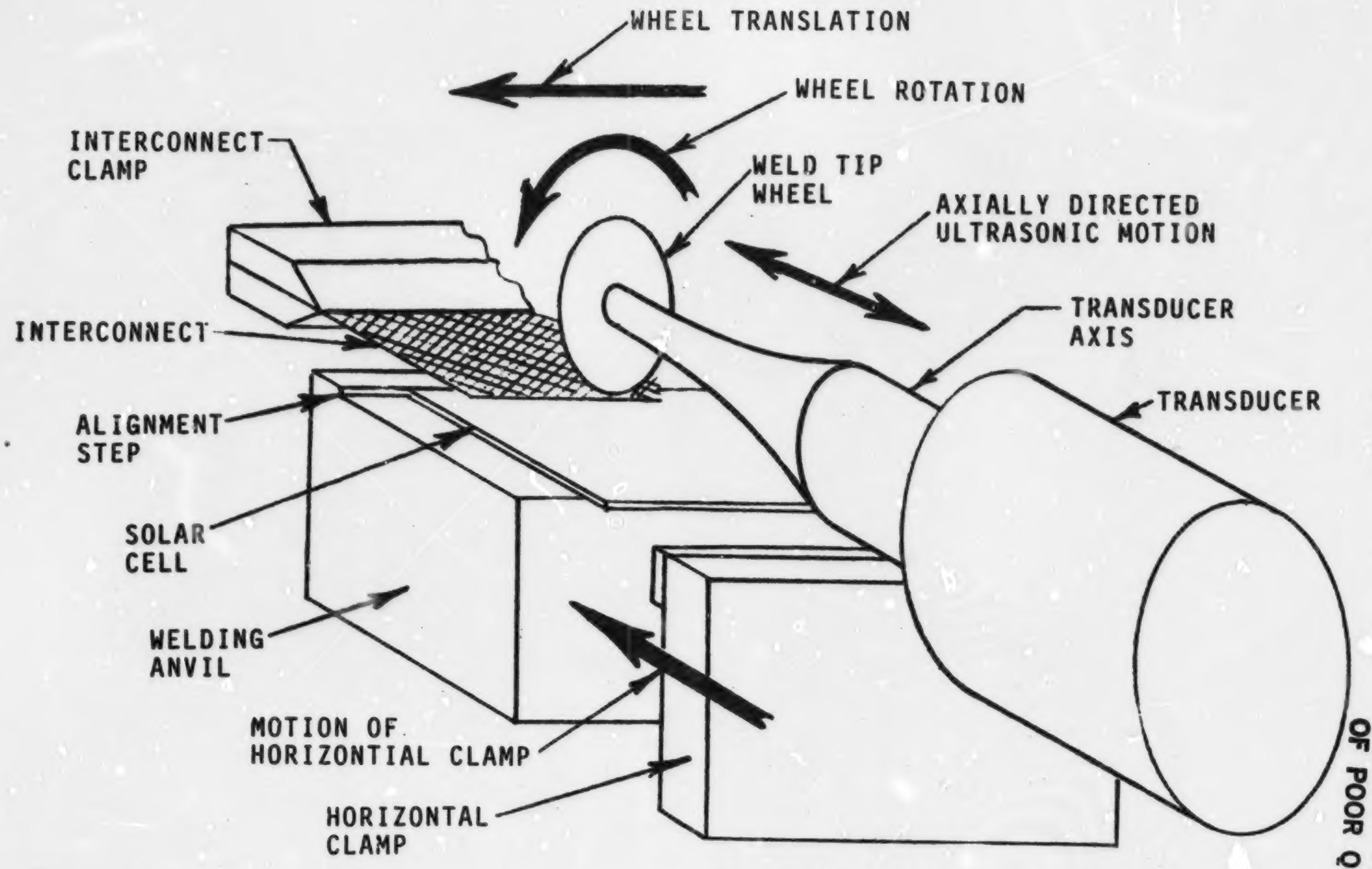
WHEEL TRANSLATION
WHEEL ROTATION
INTERCONNECT CLAMP
WELD TIP WHEEL
AXIALLY DIRECTED ULTRASONIC MOTION
INTERCONNECT
TRANSDUCER AXIS
TRANSDUCER
ALIGNMENT STEP
SOLAR CELL
WELDING ANVIL
MOTION OF HORIZONTIAL CLAMP
HORIZONTAL CLAMP

Figure 3.2-1 Schematic Drawing of an Ultrasonic Weld Station

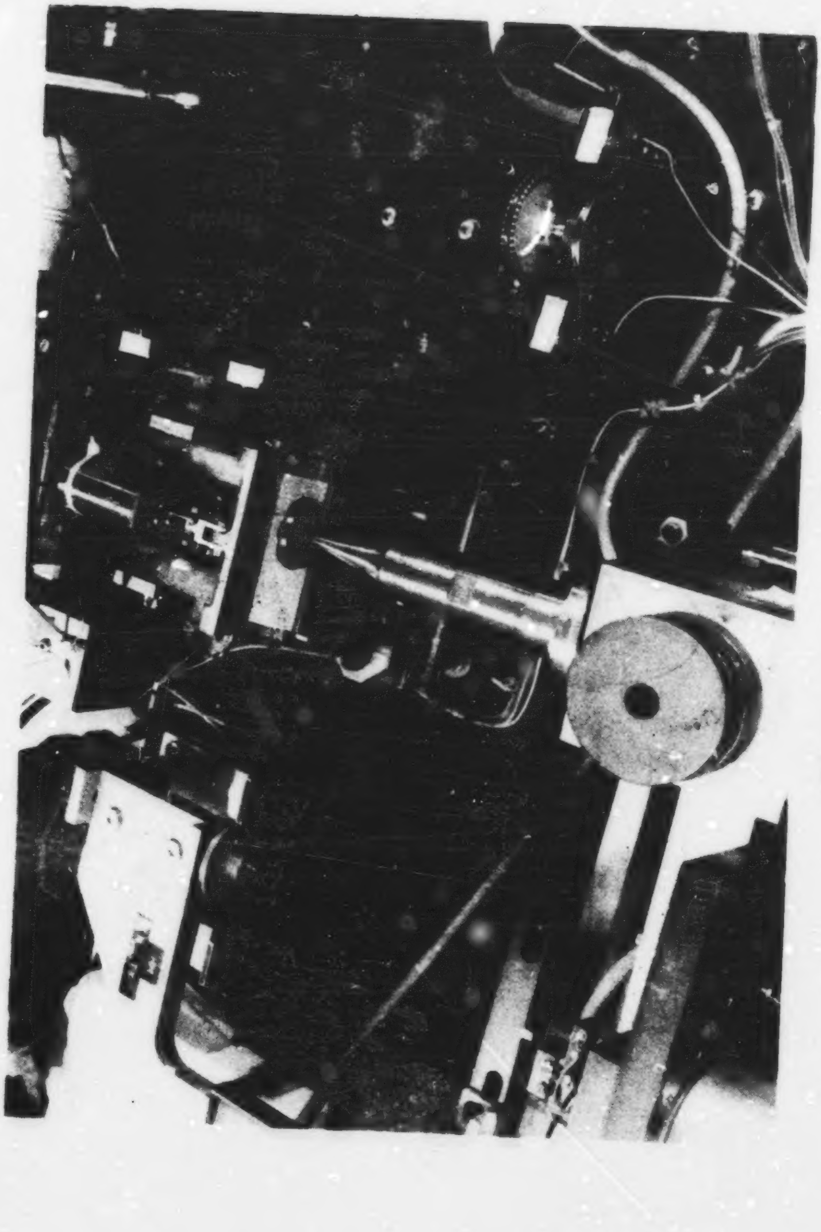

Figure 3.2-2 Photograph of an Ultrasonic Weld Station.

The ultrasonic energy is variable from a value that is essentially zero to a value that is large enough to crack silicon cells. The energy used on any particular weld is set by the appropriate control knob on the power supply for the transducer. Quantitative control over the magnitude of this energy is maintained by monitoring the AC voltage and AC current of the electrical power being generated by the power supply. This voltage and current is displayed continously on an oscilloscope as Lissajous patterns. To select a specific operating power, the power supply control knob is adjusted to produce a predetermined value of voltage within the range of 10 to 20 volts peak to peak. The power supply is from Sonobond Corporation (West Chester, PA 19380), model MS 5010-100, operating at a nominal frequency of 50,000 H_z, modified to include phase locked continuous tuning. The transducer coupler is a matching Sonoband WS 1050 (Sonobond Unit Drawing No. SB 20843, Rev. B). It is a magnetostrictive type composed of laminated nickel cobalt strips and an electrical coil. It is mechanically rugged and electrically stable.

Two of these weld stations, one for front contacts and one for back contacts, are included within the prototype machine. As such, the weld parameters can be optimized separately for front and for back contacts, if required. These two weld stations are positioned along with the appropriate mechanical transfer mechanisms for transfering cells and interconnects automatically and reproducibly so as to maintain close geometrical alignment at a high production rate.

An overall view of the prototype welding machine is shown photographically in Figure 3.2-3 and schematically in Figure 3.2-4. The sequence of operation is initiated by placing cells front side down on the initiator tray (A) (Figure 3.2-4). The operator then slides one 2x6 cm cell or three 2x2 cm cells into slots on the transfer arm (B). The edges of these slots have been precision machined to provide the first alignment control on the cells. The operator in Figure 3.2-3 has just performed this task. Next the operator opens a valve to activate the vacuum hold down of the cells on transfer arm (B). Another switch activates transfer arm (B) so that it rotates about axis (C), thus placing the cells on anvil (D) front side up.

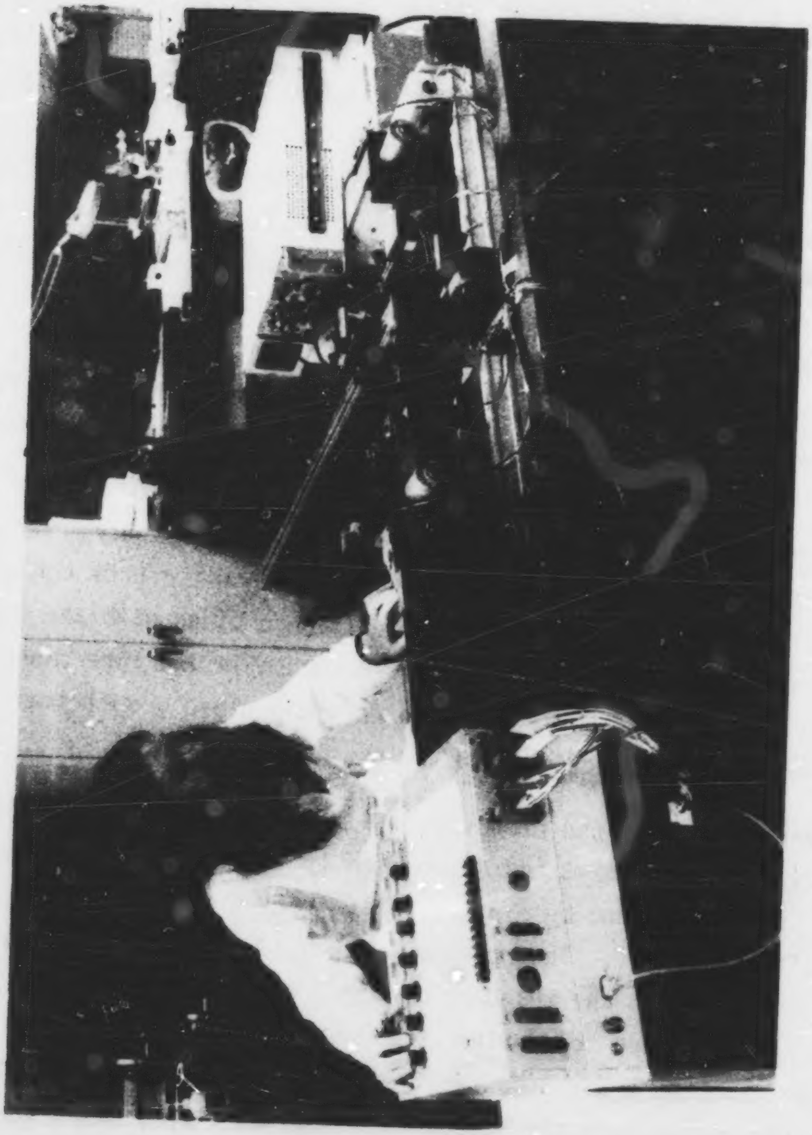

Figure 3.2-3 Overview of Ultrasonic Weld Machine.

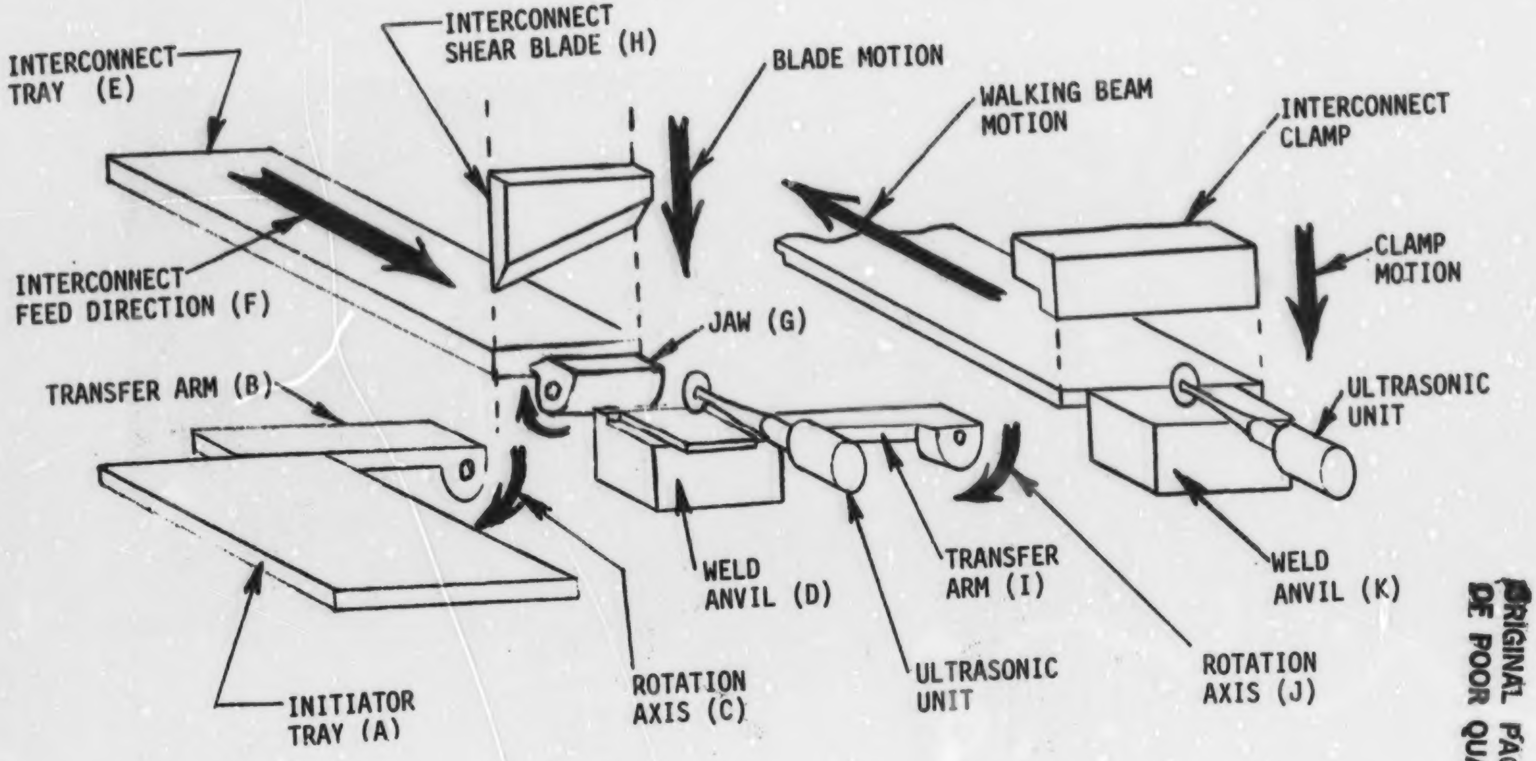
INTERCONNECT TRAY (E)
INTERCONNECT SHEAR BLADE (H)
BLADE MOTION
WALKING BEAM MOTION
INTERCONNECT CLAMP
CLAMP MOTION
INTERCONNECT FEED DIRECTION (F)
JAW (G)
TRANSFER ARM (B)
ULTRASONIC UNIT
WELD ANVIL (D)
TRANSFER ARM (I)
WELD ANVIL (K)
INITIATOR TRAY (A)
ROTATION AXIS (C)
ULTRASONIC UNIT
ROTATION AXIS (J)

Figure 3.2-4 Schematic Drawing of Ultrasonic Welding Machine

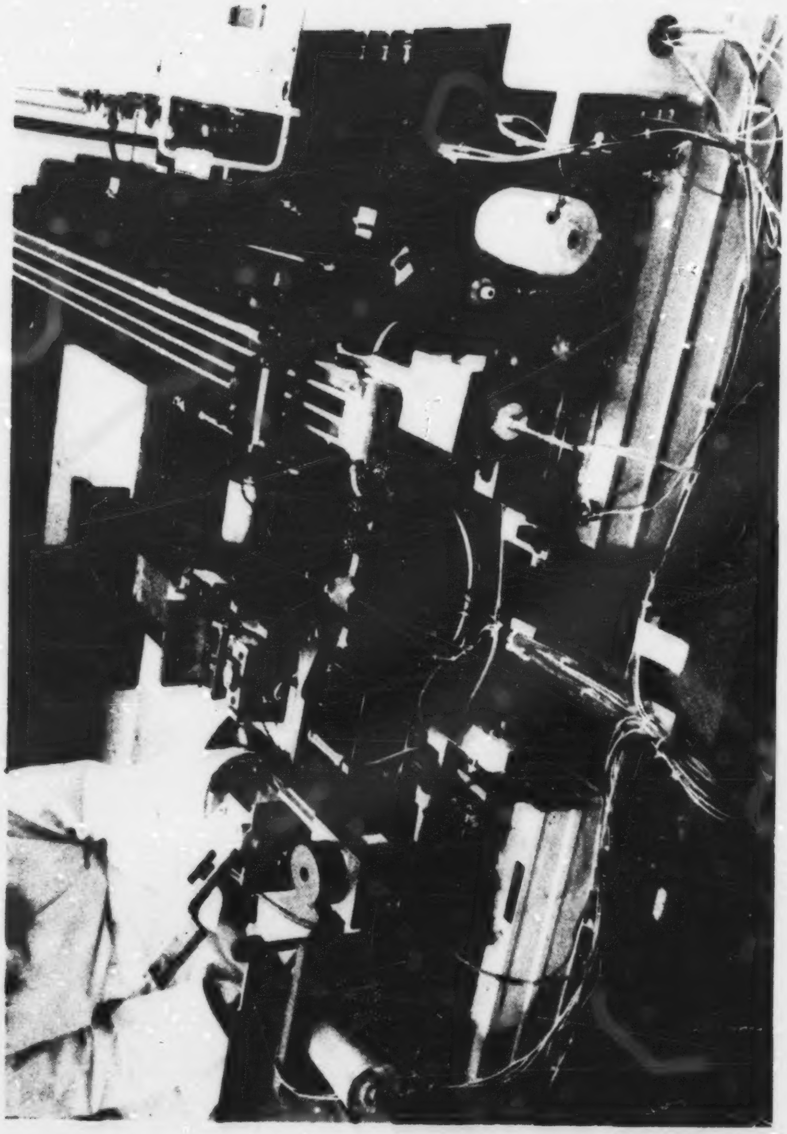

Figure 3.2-5 Initial Transfer Arm Motion.

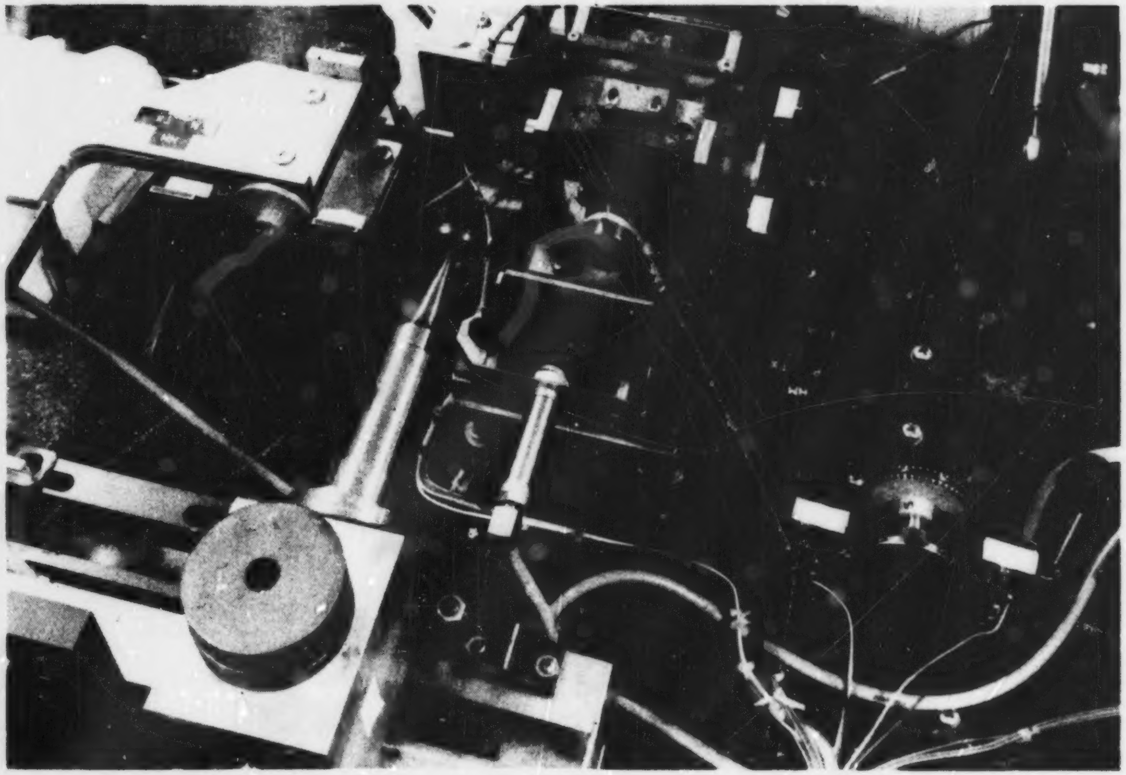

Figure 3.2-6 Cells Positioned on Weld Anvil.

Figure 3.2-6 shows this transfer arm near the beginning of its rotation. After the cells have been placed on anvil (D), the vacuum on the transfer arm (B) is released while vacuum is applied to the back of the cells to hold them on the anvil (D). The transfer arm (B) then is rotated back to its starting position next to the initiator tray (A). At the same time a horizontal clamp moves against the edge of the cell, assuring that the opposite edge of the cell is in contact with the alignment step on the anvil as shown in Figure 3.2-1. This alignment step is adjacent to the negative contact bar on the top of the cells. The position of the contact bar (the region to be welded) thus is reproducibly aligned each time with respect to the welding machine. Figure 3.2-6 shows three 2x2 cm solar cells in this aligned position on the weld anvil. The weld wheel in this photograph is in its normal resting position to the left of the anvil where it is out of the way so as not to interfere with the cell transfer. The small diameter cylinder in the foreground of the solar cells is the pneumatically operated drive for the horizontal clamp.

The next series of operations lead to placing the interconnect over the negative contact bar on the solar cells. The interconnect is derived from an uncut sheet of silver foil that has been photochemically etched to have an appropriate pattern of holes or slots to provide easy compliance in an inplane direction. This uncut foil rests on the interconnect tray (E) located behind the weld anvil (D) in Figure 3.2-4. A sheet of silver mesh on the tray is visible in the photograph of Figure 3.2-5. The interconnect placement operation starts with the movement of a cam that advances the sheet of silver foil a precise distance toward the solar cell. The silver foil thus protrudes beyond the end of the tray. The edge of this protruding foil is gripped by a mechanical jaw (G), then the shear blade (H) (Figure 3.2-4) descends and cuts an interconnect from the foil. The length of this cut interconnect is determined by the distance the foil was moved in the tray by the cam. This distance is precisely the same for each succeeding interconnect cut. After the foil has been cut, the mechanical jaw rotates 180 degrees about its axis, thereby transfering the interconnect from the edge of the tray to placement on the N contact of the solar cell. The initial position of this jaw as it grips the uncut end of foil still on the tray is shown in the upper center portion of Figure 3.2-6.

The position of this jaw after it has rotated to place the interconnect onto the solar cells is depicted in Figure 3.2-2, just behind the solar cells. Since all of these motions are controlled precisely, the interconnect is positioned on the N contact in an exact and repeatable manner. It is held in this position by the jaw throughout the subsequent welding operation.

The next series of operations produce the weld between the interconnect and the solar cell front contact bar. To start this operation, the welding tool moves from left to right (starting from the position shown in Figure 3.2-6). During this direction of motion, the tool rides on a cam which keeps the weld tip well above the cell and interconnect. After reaching beyond the right side of the solar cell, the tool drops down, then starts traveling back toward the left. During this leftward motion the wheel is allowed to rest on the cells while ultrasonic energy is directed to the weld tip. This produces the welding action between the interconnect and the solar cell. This welding phase is depicted in Figure 3.2-2. The welding tool is mounted on the end of a counterbalanced pivoting arm which maintains alignment of the tool while allowing the tool to raise or lower against gravity. The force pressing the weld tip against the interconnect is established by weights placed on top of the bearing housing for the rotating transducers. In Figure 3.2-6, four such weights are visible in the lower left portion of the photograph. During the travel of this welding phase, a series of cams lift the weld tool away from contact with the interconnect as the weld tip approaches an edge of a cell. If the ultrasonically active weld tip were allowed to be in contact with the edge of a cell, it would chip a small section of the cell at that location. After the weld tool has finished its leftward motion and thereby finished the weld, the interconnect jaw is released and then rotated backward to its initial position next to the interconnect tray. At this time the weld station is similar in appearance to that shown in Figure 3.2-6 except the interconnect is now permanently bonded to the solar cells.

At this stage of the operation, the next sequence of steps can branch along either one of two paths. On one path, the cells with interconnects are transfered by means of transfer arm (I) from weld station (D) to weld station (K) (Figure 3.2-4).

Alignment is maintained by this transfer arm so that the cells are placed onto station (K) in exactly the correct location. In the latter position they would then precede through a series of steps that would connect them in series to preceeding cells by welding the other part of the interconnect to the back of the immediately preceeding cells. This would be the path taken if the cells already had a coverglass before starting welding (with the cover being undersize to keep the front contact exposed for welding) or if the covers were not to be put on the cells until after all welding was completed.

The alternate path would remove the cells from the welding machine by hand after the front contact had been made. They then would have covers bonded to the front with silicone adhesive. After cure of the adhesive the cells would be placed onto weld anvil (K) by hand. To achieve a precise location of the cells on anvil (K) with this hand operation, a small alignment frame is added to the anvil so that the cells fit precisely within pockets. Once the cells are on the anvil, they then are joined in series to preceding cells by welding the outer part of the interconnect to the back of the immediately preceding cell.

The welding operation to the back of a cell starts with the cell in position on anvil (K), with the front side of the solar cell resting on the anvil surface. The interconnect, which has already been bonded to the front bar contact of this cell (cell A), extends over the back of the preceding cell (cell B), as shown in Figure 3.2-7. Before the welding operation starts, a clamp is lowered over the outer edge of this interconnect, thereby keeping the interconnect from cell A firmly held against the back of cell B. Welding then is performed to the back of cell B along the dashed line indicated in Figure 3.2-8. This welding operation is identical to that described for the front contact weld. After the back weld is completed, the interconnect and cell hold down clamp moves backward in unison with the walking beam until cell A is moved to the position previously occupied by cell B and cell B advances to the position previously occupied by cell C. The clamp then is released, and the clamp and walking beam return to their initial position.

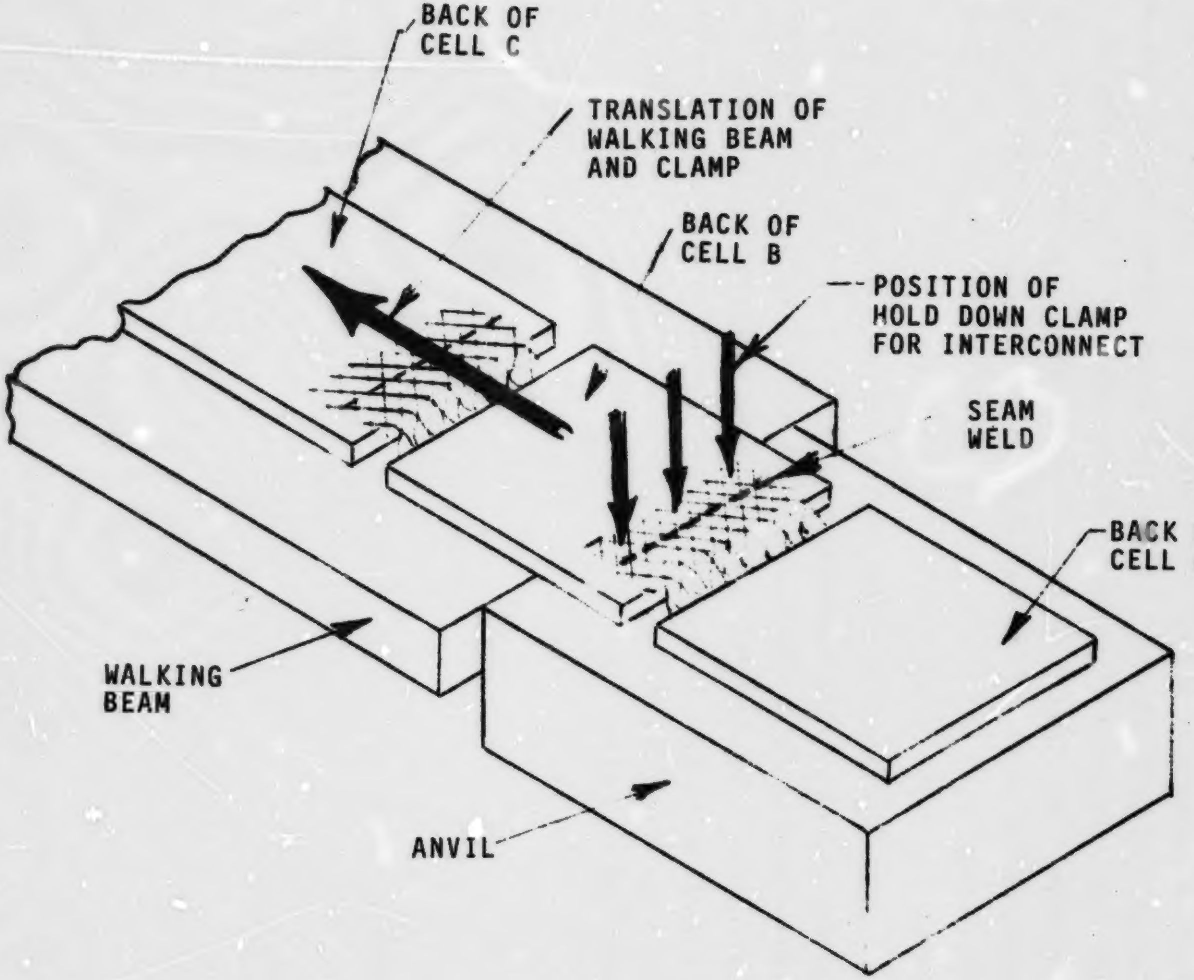
BACK OF
CELL C
TRANSLATION OF
WALKING BEAM
AND CLAMP
BACK OF
CELL B
POSITION OF
HOLD DOWN CLAMP
FOR INTERCONNECT
SEAM
WELD
BACK OF
CELL A
WALKING
BEAM
ANVIL

Figure 3.2-7 Welding of Cells in Series.

The stage is thus set for a new cell to be placed on anvil (K) in preparation of repeating the entire welding sequence. By repeating this process over and over, a long string of series connected solar cells is formed. The translation distance of the walking beam and clamp is adjusted to achieve a precise cell to cell spacing. Figure 3.2-8 shows a photograph of this weld station with three series strings of 2x2 cm solar cells lying along the walking beam. The clamp is in the raised position. The welding tool is to the right of the anvil. Figure 3.2-9 shows a photograph of this same weld station, except here the clamp is in the down position and the welding tool is moving across the interconnect forming a weld.

In summary, the cells are welded into series connected strings by first having one edge of a foil interconnect welded to the front contact of a cell and then having the other edge of the interconnect welded to the back of the preceding cell. For adapting this machine to handle ultrathin solar cells, an examination has been made of the forces imposed on the cells by welding and also the forces imposed by the transfer and alignment mechanisms. This is described in Section 3.4.

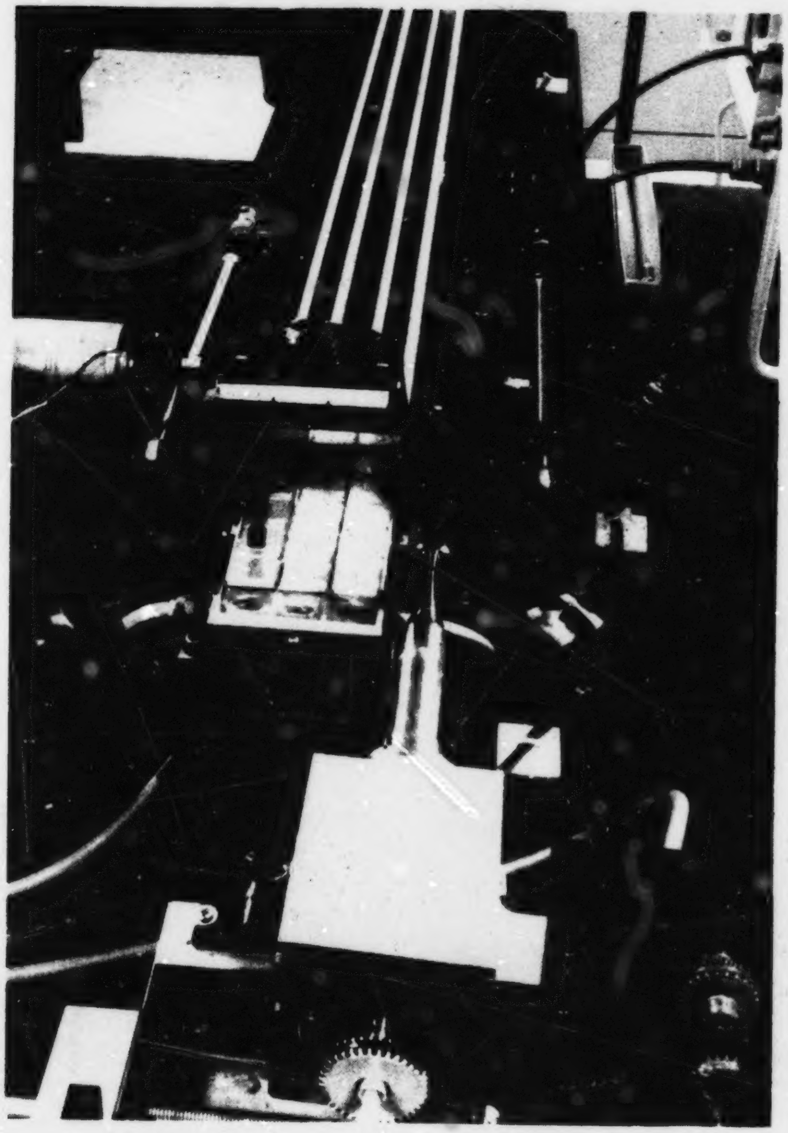

Figure 3.2-8 Weld Station K in Open Position.

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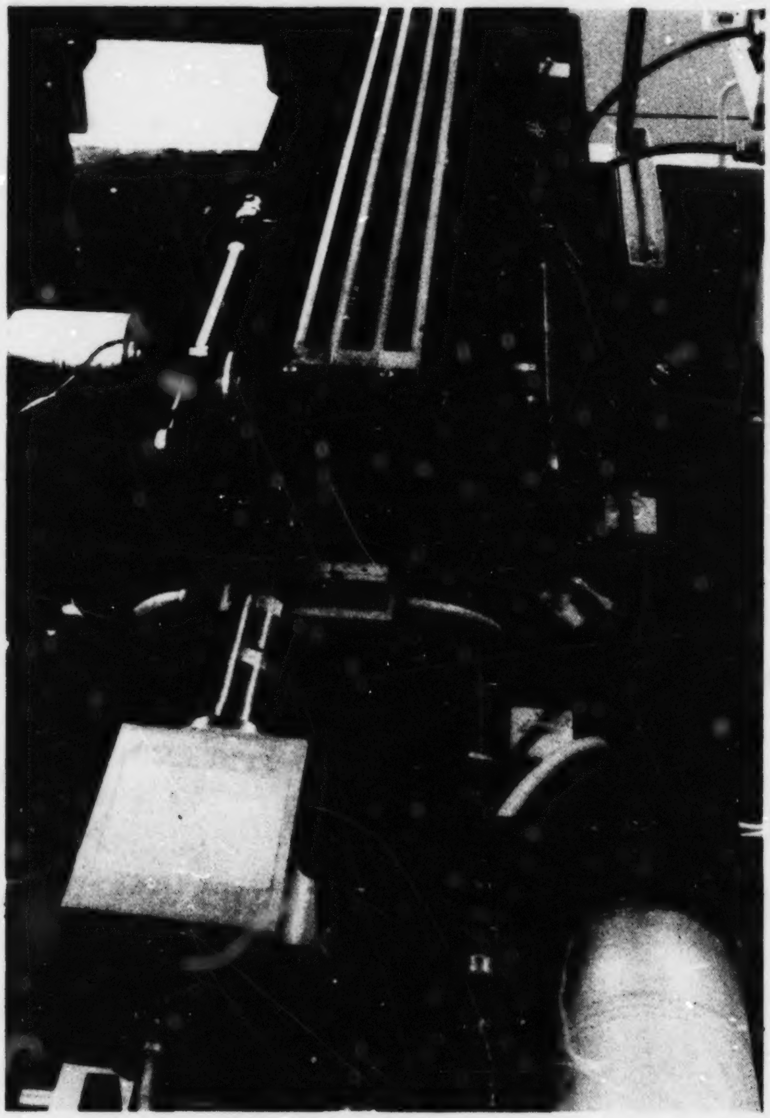

Figure 3.2-9 Weld Station K in the Welding Positon.

3.3 TEST COMPONENTS

3.3.1 Solar Cells

The welding optimization phase of this program was conducted on cells of various thickness, starting with cells 0.20 mm thick and working down to the ultrathin (0.07 mm) cells. The lot of ultrathin cells was furnished by JPL. These cells had been manufactured by Spectrolab. The other cells were purchased from Applied Solar Energy Corporation (ASEC). These later cells were procured in three lots having nominal thickness of 0.20 mm, 0.15 mm, and 0.10 mm, respectively. The characteristics of all four lots of cells are summarized in Table 3.3-1. All four lots of cells had bar type front contacts for maximum compatability with seam welding. The ultrathin cells as well as the thickest lot of the ASEC supplied cells had a back surface field made by the aluminum paste process and therefore were relatively rough. The other two lots of ASEC cells had a back surface field produced with a boron process and were smooth. The overall silicon surface finish on the two thickest lots were smooth. The silicon surface finish on the two thinnest lots was dimpled (with dimple diameters up to 0.4 mm) as a result of the type of chemical etching used to make these cells thin. The fronts of the four types of cells are shown photographically in Figure 3.3-1. The backs of these four cells are shown photographically in Figure 3.3-2. The back surfaces of the two cells of intermediate thickness in Figure 3.3-2 appear dark as an artifact of the photographic lighting. These surfaces are smooth and reflect light specularly. This same lighting artifact tends to emphasize the presence of small scratches on the silver surface produced when the cells were placed in a fixture to measure their photovoltaic response. The thinest and thickest cells have a mat finish on their back surface so that light is reflected in a partially diffuse manner.

PARAMETER	CELL TYPE			
	A	B	C	D
MECHANICAL				
CELL DIMENSIONS				
● THICKNESS				
AVE. (mm)	0.078	0.121	0.179	0.212
-2S (mm)	0.064	0.100	0.158	0.212
+2S (mm)	0.090	0.144	0.201	0.231
● WIDTH (mm)	20.0	20.0	20.0	20.0
● LENGTH (mm)	20.0	20.0	20.0	20.0
EDGE FINISH	LASER & BREAK	SAW & BREAK	SAW & BREAK	SAW & BREAK
BACK FIELD	ALUMINUM PASTE	BORON DIFF.	BORON DIFF.	ALUMINUM PASTE
BACK REFLECTOR	ALUMINUM	ALUMINUM	ALUMINUM	ALUMINUM
CONTACT THICKNESS(um)	3-6	3-7	3-7	3-7
N BAR WIDTH (mm)	1.0	0.6	0.6	0.6
ELECTRICAL				
(AVE., AT 28^{O}C, AMO ILLUMINATION)				
SHORT CIRCUIT CURRENT, I_{sc} (mA)	150	156	158	165
CURRENT AT VOLTAGE OF 475 mV, (mA)	139	144	144	156
OPEN CURCUIT VOLTAGE, V_{oc}(mV)	584	590	586	604
MANUFACTURER	SPL	ASEC	ASEC	ASEC

Table 3.3-1 Solar Cell Types

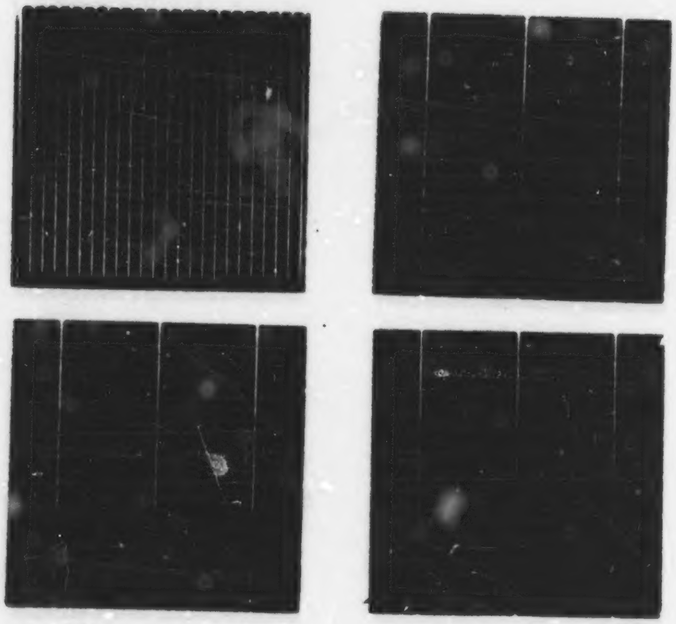

Figure 3.3-1 Four Types of
Solar Cells (Front)

Type A Type B

Type C Type D

(refer to Table 3.3-1 for cell descriptions)

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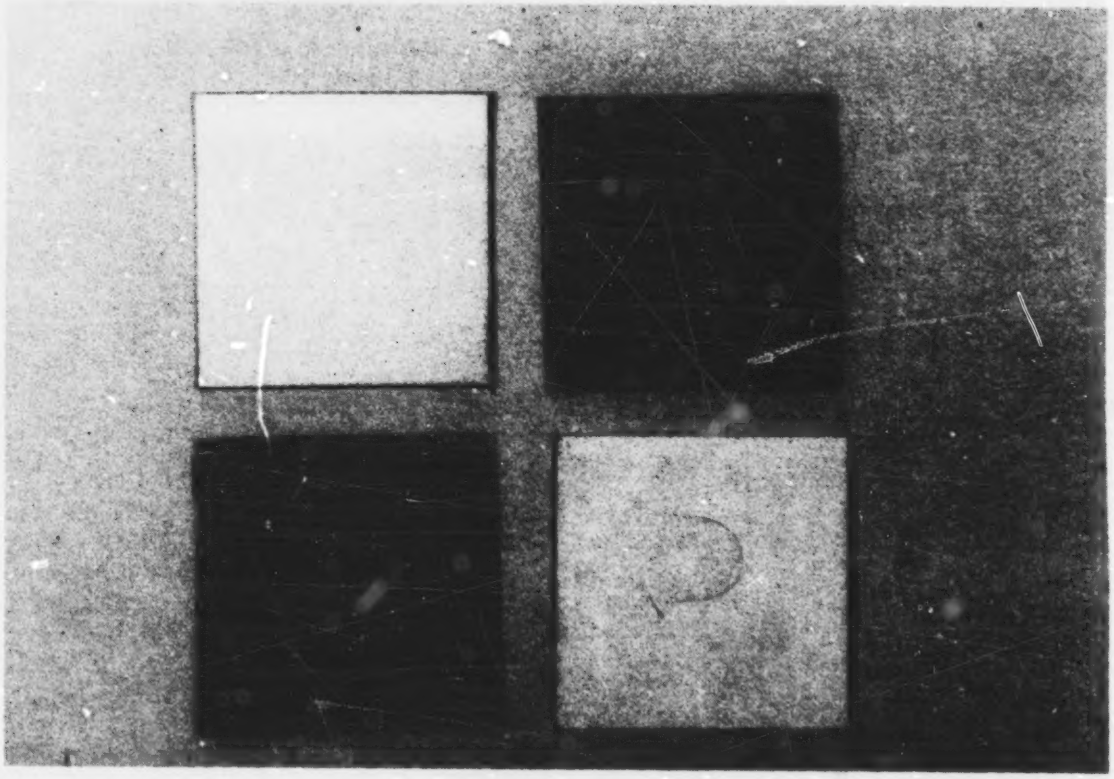


Figure 3.3-2 Four Types of
Solar Cells (Back).

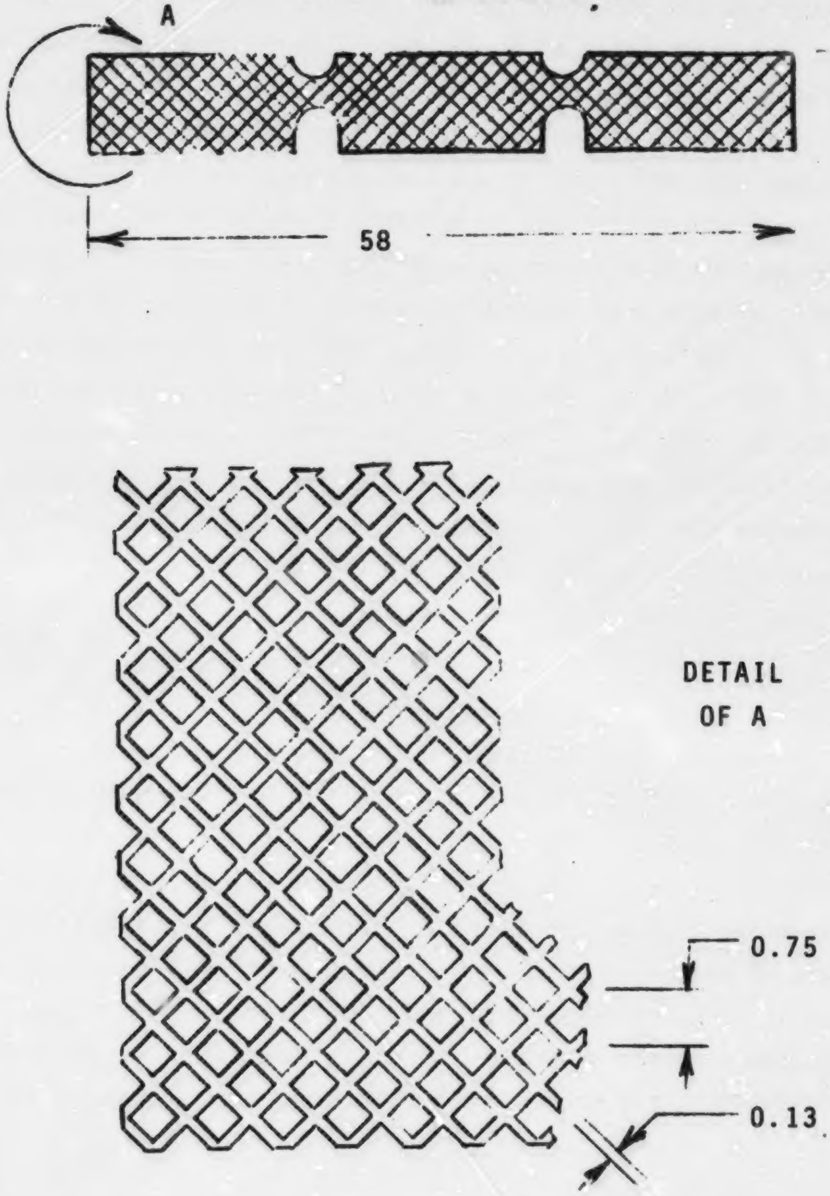
Type A	Type B
Type C	Type D

(refer to Table 3.3-1 for cell descriptions)

3.3.2 Interconnects

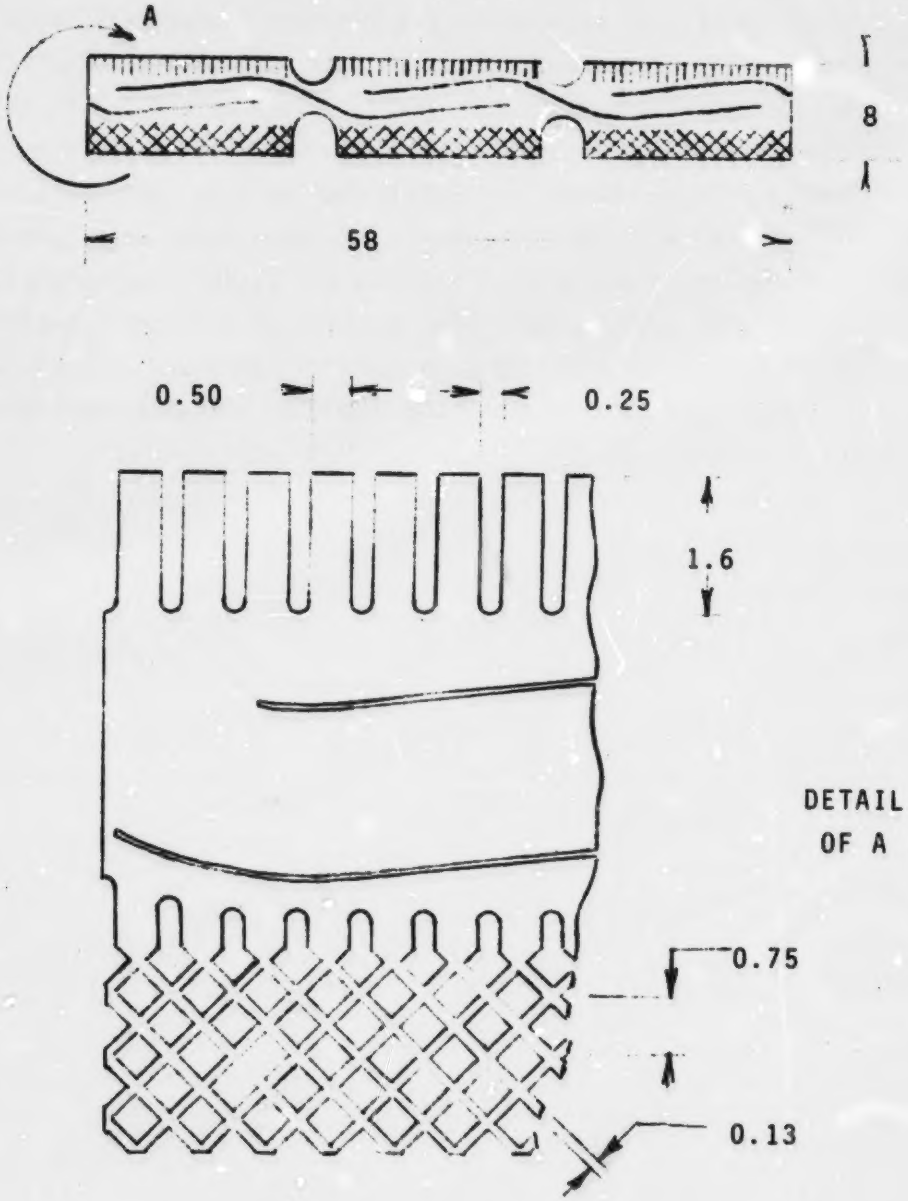
The principal interconnect configuration used during this welding investigation was a diamond mesh pattern etched from photographically masked 0.025 mm thick foils of pure silver. During the early part of the investigation another type of foil interconnect configuration also was used, that having an S shaped slot etched into the center section, with a mesh along one edge and a row of small tabs along the other edge. This alternate interconnect also was etched from 0.025 mm thick silver foils. These interconnects were chosen because they are similar to soldered interconnects already used on flight hardware. They thus had a history of use that provides background confidence. The mesh pattern dimensions are detailed in Figure 3.3-3. The dimensions of the tabs on the second type of interconnect are detailed in Figure 3.3-4. Either type of pattern welded satisfactorily to the thick cells where a large welding force could be applied without damaging the cells. For thin cells, which could tolerate only a limited force application, the mesh pattern provided a stronger weld. For the latter part of the program the mesh patterned interconnect was used exclusively.

Two other types of interconnect foil materials had been considered at the start of the program: silver foil 0.015 mm thick and silver plated Invar foil. The first of these would be slightly lighter in weight as well as slightly easier to weld. There would also be slightly lower stress build-up under thermal cycling. The Invar foil would be advantagous for lower thermal expansion mismatch between the interconnect and solar cell. However, at the start of this program neither of these latter two materials were readily available in the small quantities required for their timely inclusion in this program. As the program progressed, the 0.025 mm thick silver mesh proved satisfactory, and therefore the alternate materials were not pursued further.


A
8
58
DETAIL
OF A
0.75
0.13

Dimensions are in millimeters.

Figure 3.3-3 Mesh Style
Interconnect for 3 Cells in Parallel


A
8
58
0.50
0.25
1.6
DETAIL
OF A
0.75
0.13

Dimensions are in millimeters.

Figure 3.3-4 Inplane Flexture Style Interconnect for 3 Cells in Parallel.

3.3.3 Covers

Glass covers appropriate for the ultrathin solar cells also were provided by JPL. These were made as an experimental lot by Optical Coating Laboratories, Incorporated (OCLI). They were 0.050 mm thick (+0.020 mm, - 0.010 mm at 2 σ limits), they were fabricated from Corning 7940 fused silica by chemically etching them to final thickness. The surface was rough, giving a frosted appearance. Because these were experimental covers, there was no ultraviolet blocking nor visible antireflective coating on their surfaces. Thus, the covers were not of a flight representative configuration but were supplied as mechanical samples that could be used to investigate covering processes that would be suitable for ultrathin covers on ultrathin cells.

3.4 MACHINE MODIFICATIONS

The initial part of the program investigated the ability of the mechanisms of the machine to transport and align the ultrathin solar cells without damage. Earlier work had already demonstrated that cells of conventional thickness would not be damaged. In the present program, however, it soon became apparent that the welding machine would require modifications to accommodate the ultrathin cells

The fragility of the ultrathin solar cells was first noticed even before they were placed onto the welding machine. These cells had arrived in vertically slotted styrofoam trays similar to those used for cells of conventional thickness. Removal of cells from such trays normally is done by hand using plastic tweezers to grip the cell. With cells of conventional thickness, the cells can be removed or replaced into the slots without damage. If a corner of a conventional cell snags by being accidentally impressed into the soft foam material, the force required to attempt to move the cell against this obstacle is readily felt long before the force becomes large enough to break the cell. Corrective action, therefore, can be taken by the operator's hand to avoid damage to the cell. With the ultrathin cells, on the other hand, a similar snag can easily lead to breaking a chip from the corner of the cell at a force so low as to be nearly imperceptible to the hand. Furthermore, it appears that such snags occur more readily with the ultrathin cells, presumably because the thin edge can penetrate into the soft foam more readily than a thick, blunt edge.

During future programs, avoidance of this handling induced breakage can be achieved by two means. First, as the operators' experience with these cells increases, a sensitivity to handling them will be developed, thereby reducing breakage. For example, even with the relatively few cells handled during the present program, operator skill increased with experience and there was a marked decrease in breakage as the program progressed. The other factor that could reduce breakage in the future would be to use a different configuration of tray for shipping and storage. For example, the use of trays fabricated from embossed, solid sheets of plastic film would eliminate the chance of a corner snagging since the sheet plastic would be too firm to permit ready penetration by the solar cells. Furthermore, by having the cells lying flat within shallow depressions rather than placed vertically in narrow slots, the cells could be removed readily with a rubber tipped vacuum tool rather than with plastic tweezers. The vacuum pencil is quite gentle, and breakage could become nil.

The movement of the ultrathin cells by the transfer mechanisms of the modified welding machine proved to be less damaging than manual transferring, presumably because the machine movements could be made with great precision. To accommodate the ultrathin cells without breakage, the vacuum hold down ports on the transfer mechanisms were reduced in size and the partial pressure of the vacuum system was modified. These changes permitted the ultrathin cells to be transferred with a grip sufficient to maintain close tolerance control on the position of the cell, yet not so forceful as to break the cells. The transfer of cells following the P contact weld, as indicated in Figure 3.2-8, was initially of concern. However, breakage here also was eliminated by providing proper control of the pressure in the vacuum system.

The only part of the welding machine that presented any continuing problem was the horizontal clamp on the N contact welding station. The function of this clamp is to hold the cell against the locating lip, as indicated in Figure 3.2-1. During normal operation, this clamp moves toward the cell, then away from the cell at the appropriate times. This motion is controlled by a set of cams and springs. With cells of conventional thickness, this mechanism works well without damaging the cells. With ultrathin cells, however, the automatically applied force is so great as to cause the cells to buckle. While the buckled cells did not actually break, it seemed prudent to eliminate this buckling. This was accomplished by releasing part of the tension on the spring and using a manually controlled override of the cam system. This manual operation was adequate for the quantity of cells welded on the present program. For future mass production on ultrathin cells, the cam mechanism will be modified to apply the horizontal force more gently yet in an automatic manner.

The overall conclusion in working with the ultrathin cells on the automated welding machine is that the cells could be handled satisfactorily under mass production conditions. Upon completing the modifications indicated in the preceding paragraphs, the machine was able to handle the ultrathin cells routinely without cracking. Furthermore, the modified machine had no difficulty producing welds on the thick cells that were every bit as strong as those that had been produced previously on the unmodified machine. Thus, the machine in its final modified form could be used on either thin or thick cells. There was no need to reconfigure the machine each time a cell of different thickness was inserted into the machine.

3.5 WELD TESTS

The welding tests conducted on this program were divided into three categories: preliminary tests, factorial matrix tests, and surfact treatment tests. The preliminary tests were conducted principally to support the machine modification task. However, the data thus generated also provided information on the appropriate range of welding perameters that should be used and on the configuration for the interconnect. The factorial matrix tests provided the majority of data used to determine the optimum conditions of weld force, weld energy and weld speed to be used for the various thicknesses of cells. The surface treatment tests investigated whether or not the weld strength could be increased by modifying cell contact or interconnect surface finish before starting the welding operation.

3.5.1 Preliminary Tests

The preliminary tests demonstrated that the welding parameters of weld energy, weld force, and weld speed found previously to be important for the machine before it was modified were also the important parameters for the machine after modification. Thus, we were able to use much of our previous welding experience as a foundation for this ultrathin cell program.

As indicated previously, the machine was modified during this preliminary phase so that it could handle sequentially cells of all thickness without the need to reconfigure the machine each time to fit separate thicknesses. This modification prepared the way for the subsequent factorial matrix tests wherein it was possible to compare results of varying weld force, speed, and energy without compromising these comparisons with the introduction of other machine configuration changes.

The ultrathin solar cells received from JPL had a slight curvature, the front side being convex, the back side concave. This curvature apparently is a result of the manner in which the cells are manufactured. The thermal processing to put the P+ layer on the back of the cell and then the subsequent process of putting a silver layer over this introduces a stress which flexes the thin cells slightly. This curvature caused no problem with welding of interconnects. The thin cell were sufficiently flexible to conform to the holding fixtures and the anvils of the welding machine and the curvature did not interfere in any way with the welding process.

The preliminary tests also were used to select the interconnect configuration. The mesh pattern depicted in Figure 3.3-3 was chosen after it demonstrated a more consistent pull strength when welded at the light weld forces required for the ultrathin cells. Each weld bond was 0.18 mm long, formed at 45 degrees across each strand of mesh. When welds were attempted at a similar light force on the wider (0.50 mm) tabs of Figure 3.3-4 the bonds were strong along the edges of the tab but weak in the center. For this reason, the mesh type configuration was chosen for exclusive use in the subsequent matrix tests.

3.5.2 Matrix Tests

The welding matrix tests were conducted to cover economically a multitude of weld variables in a statistically significant manner. From previous experience it was known that welding to the front contact generally is more difficult than welding to the back contact. For this reason, the front contacts were welded in the matrix tests.

The form of matrix used was a full 4 x 2 x 2 x 2 format covering cell thickness (4), weld speed (2), weld energy (2) and weld force (2). Four separate matrices were used with overlapping values of the variables. The values of the variables were chosen near the optimum values based on the previous preliminary tests. An example of one of these matrices is depicted in Table 3.5-1. The numerals within each matrix box represent the time order sequence of the welds. This sequence was chosen as a means of randomizing the matrix so that the results achieved would not be biased by any learning factor that could have occurred as the welding proceeded. Three cells were welded for each of the 32 matrix factor combinations.

The range of variables included in the four factorial matrices are summarized in Table 3.5.2. The welds made with this set of matrices were evaluated with microscopic examination, with measurement of their photovoltaic power response, and with mechanical pull tests. Within Matrix I, mechanically strong bonds were obtained on all cells, and there was no measurable degradation in the photovoltaic response. However, microscopic examination revealed that some of the ultrathin cells had fine cracks near a portion of their welded areas, as indicated schematically in Figure 3.5-1. At this time it was suspected that these cracks were caused by the ultrasonic energy (transducer voltage) being too high. To confirm this suspicion, Matrix II was run at

TRANSDUCER VOLTAGE	CELL SIZE WELD SPEED / FORCE	2 MIL (CELL TYPE A)		4 MIL (CELL TYPE B)		6 MIL (CELL TYPE C)		8 MIL (CELL TYPE D)	
		0.7 cm/s	1.0 cm/s	0.7 cm/s	1.0 cm/s	0.7 cm/s	1.0 cm/s	0.7 cm/s	1.0 cm/s
15.0 V	360 g	12	28	19	15	30	22	1	5
	460 g	20	24	10	27	3	6	29	13
17.5 V	360 g	4	7	31	23	11	14	17	25
	460 g	32	16	2	8	18	26	9	21

Table 3.5-1 Representative Welding Test Matrix
(Numerals in boxes indicate the time sequence of tests)

	MATRIX I	MATRIX II	MATRIX III	MATRIX IV
CELL TYPES, PER TABLE 3.3-1	A,B,C&D	A,B,C&D	A,B,C&D	A,B &C
TRANSDUCER EXCITATION, (VOLTS)	15.0 & 17.5	20.0 & 22.5	12.5 & 15.0	12.5 & 15.0
CLAMPING FORCE, (GRAMS)	460 & 560	460 & 560	360 & 460	260 & 360
WELDING HEAD SPEED, (CM/SEC)	0.7 & 1.0	0.8 & 1.3	0.8 & 1.3	0.8 & 1.3

Table 3.5-2 Welding Parameters for the Four Principal Matrices.

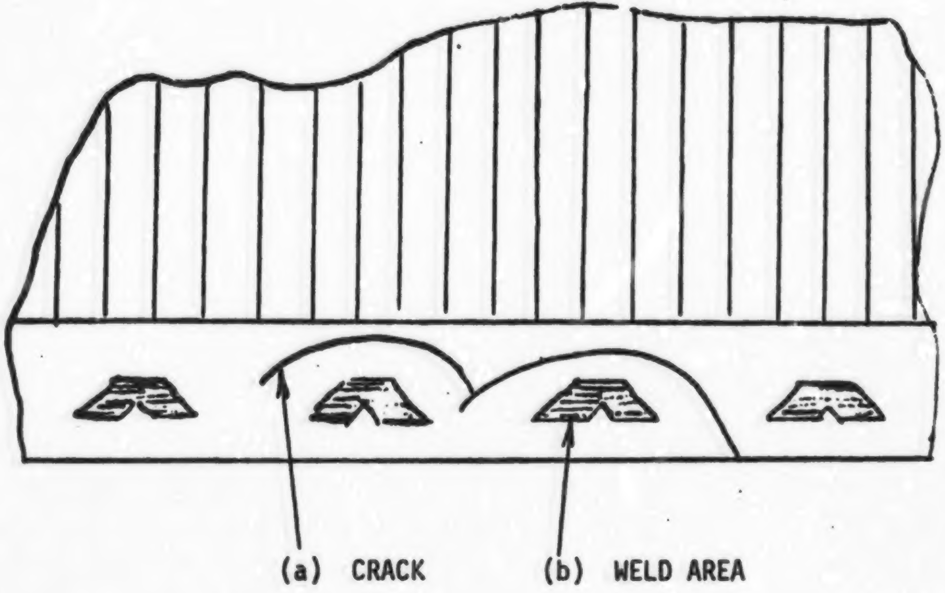

(a) CRACK
(b) WELD AREA

Figure 3.5-1 Schematic of Cracked N Contact

even higher energy levels in order to exaggerate such an effect. The welds produced with this matrix were similar to those of Matrix I: good mechanical bonding on all cells, no measurable electrical degradation, but a few cracks appearing on the ultrathin cells. The number of cracks, however, was no greater for Matrix II than for Matrix I.

Matrix III was run with less weld energy and force. The results were similar to those of Matrix I and Matrix II except that the pull strength was not as great, while on the other hand there were fewer cracks in the ultrathin cells. Matrix IV was run with less force. With this matrix only one ultrathin cell developed a crack. The mechanical pull strength of these lightly welded cells was not as great as for the preceeding matrices but was judged adequate for practical application on solar arrays.

Welds also were made to the back of cells, again using a variety of weld schedules. As anticipated from our previous experience with thick (0.20 to 0.25 mm) cells, the success of these welds was much less sensitive to variations in weld parameters. Welding parameters similar to those of Matrix I and Matrix III were used on cell backs without producing cracks in any of the cells, including ultrathin cells. These welds were all mechanically strong. The weld conditions of Matrix IV when used for welding to the backs of cells also did not produce any cracks. The mechanical strength of these latter welds was somewhat greater then when similar weld parameters had been used on the front. Welds were made successfully to the back of uncovered cells and also to the back of cells that had covers of 0.050 mm thick fused silica bonded to the front of the cell with clear silicone adhesive.

3.5.3 Surface Finish

All of the weld tests described previously were performed with cells and interconnects having surfaces that were essentially in the condition as received from the manufactures. The only treatment that had been given to these cells before welding was to clean them with isopropyl alcohol to remove a light film of oil that had contaminated some of the cells. The silver interconnect mesh was not given any preweld treatment, merely used as it was received from the supplier. The use of unmodified surfaces for most of the welding tests arose from the desire to have the resultant weld process be suitable for future application where a large quantity of cells would be handled in a mass production.

manner. As indicated in section 3.5.2, satisfactory welds were obtained with these untreated surfaces. However, with the light welding force required for the ultrathin cells to avoid forming cracks, the welds on these untreated surfaces were not as mechanically strong as was possible with heavy welding force. In an effort to determine if stronger welds could be produced, the contact surface of some cells were modified before welding. One such modification was to rub the contact surface with a few light strokes using a soft, pink rubber eraser (Parapink No. 7011, Faber Castell). This treatment simultaneously cleaned and produced fine scratches. The other surface modification treatment was similar except that a glass fiber brush was used instead of a rubber eraser. A matrix of weld tests was run using all combinations of the variables shown in Table 3.5-3. The results indicated that both the rubber eraser and the glass brush treatments led to welds that were slightly stronger than were achieved with the untreated surface. Thus, for thick cells, where a heavy weld force can be used without damage, welding solar cells in their simple untreated form would be economical and adequate. For the ultrathin cells, the optimum weld schedule would include a light brushing of the contact areas with a glass fiber brush before forming the weld. The glass brush would be prefered over the rubber erasure because brushing needs only a negligible force on the cell. The risk of cracking a well supported ultrathin cell while brushing it with a glass fiber brush is negligible. Furthermore, the brushing operation could be automated readily, substituting a rotating, circular brush for the hand held pencil type brush used in this project.

3.5.4 Thermal Shock

The ability of these welded cells to survive thermal excursion was investigated by subjecting some of them to both high and low temperature. Cells with interconnects welded on the N contact were cycled between - 196°C and + 150°C for 10 cycles. A dwell time of 10 minutes was used at each temperature extreme. After cycling, the cells were examined microscopically and with mechanical pull tests of the weld bond. There was no evidence of any degradation resulting from these temperature excursion tests.

3.5.5 Test Results

The several tests performed on evaluating the welding of these solar cells provide an overview on the practicality of using ultrasonic welding.

CELL TYPES	TYPE A, TYPE B
CONTACT TYPES	FRONT, BACK
SURFACE TREATMENT	AS RECEIVED, RUBBER ERASER, GLASS BRUSH
WELD SPEED	0.8 cm/sec, 1.3 cm/sec
ULTRASONIC EXCITATION	12.5 volts 15.0 volts
CLAMPING FORCE	260 grams 360 grams

Table 3.5-3 Test Matrix Elements for Investigating Surface Treatment Effects

The critical step in forming a series interconnected string of cells is making the weld to the N contact. For this reason most of the testing focused on obtaining the optimum conditions for forming this weld. A representative string of solar cells is depicted schematically in Figure 3.5-2. The recommended assembly steps for forming this string are presented in Figure 3.5-3.

An example of an interconnect satisfactory bonded to an ultrathin solar cell is shown in Figure 3.5.4. The interconnect has been placed in correct spatial alignment over the N contact by the automated transfer mechanism of the welding machine. Furthermore, the clamping mechanisms have held both cell and interconnect in this correct alignment throughout the entire vibratory period in which the seam was being formed. The seam welder passed sequentially over almost all strands of the mesh along a line running up the mid-width of the 1.0 mm wide N contact bar. The only strands not welded are a few at the start and finish of this seam line where the welding wheel was lifted above the cell by the cam mechanism so that the ultrasonically active wheel would not touch the edges of the cell.

A second representative welded N contact is shown in Figure 3.5-5. The only difference from that of the preceeding Figure is in the position of the cut edge of the mesh relative to the intersection nodes of the mesh. This variation in mesh edge shape had no measurable effect on the quality of the weld. The position of the weld line with respect to the center line of the solar cell N contact remained constant from cell to cell. The strength of the weld did not depend measurably on whether the welds went along the mesh nodes or along the individual strands between nodes. An example of the welds running along the mesh nodes is shown in Figure 3.5-6.

The mechanical strengths of the weld bonds were tested by pulling them with a Unitek Model 6-092-03 controlled rate tensile machine using a Chatillion force gage with 1 kg full scale (0.01 kg least division). The travel rate of the force head was 1.6 mm/sec. During the preliminary tests (section 3.5.1) several different configurations of pull tabs were investigated, including some especially formed tab shapes. The chosen configuration was a simple 3.0 mm wide strip of standard interconnect mesh. To obtain these pull tabs, welds were made to the N contact using normal 19 mm wide mesh as shown in Figure 3.5-4. After welding the central 12 to 15 mm portion of this mesh, the mesh was cut into 4 to 5 strips as indicated in Figure 3.5-7.

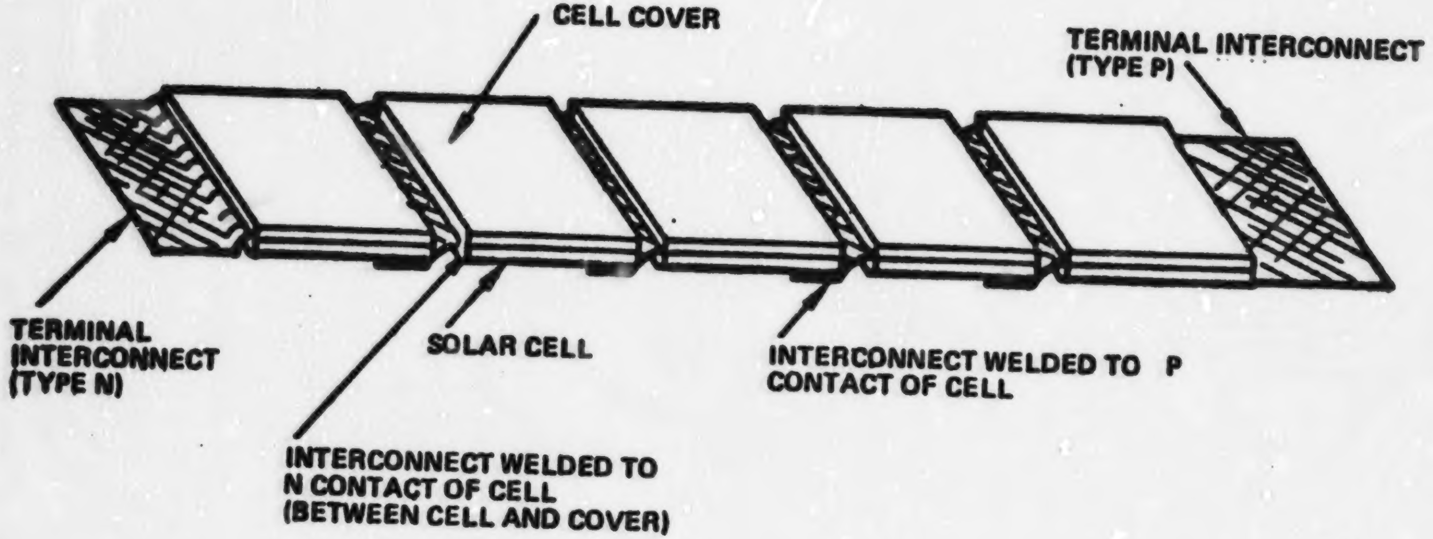

CELL COVER
TERMINAL INTERCONNECT (TYPE P)
TERMINAL INTERCONNECT (TYPE N)
SOLAR CELL
INTERCONNECT WELDED TO P CONTACT OF CELL
INTERCONNECT WELDED TO N CONTACT OF CELL (BETWEEN CELL AND COVER)

Figure 3.5-2 Representative Solar Cell String.

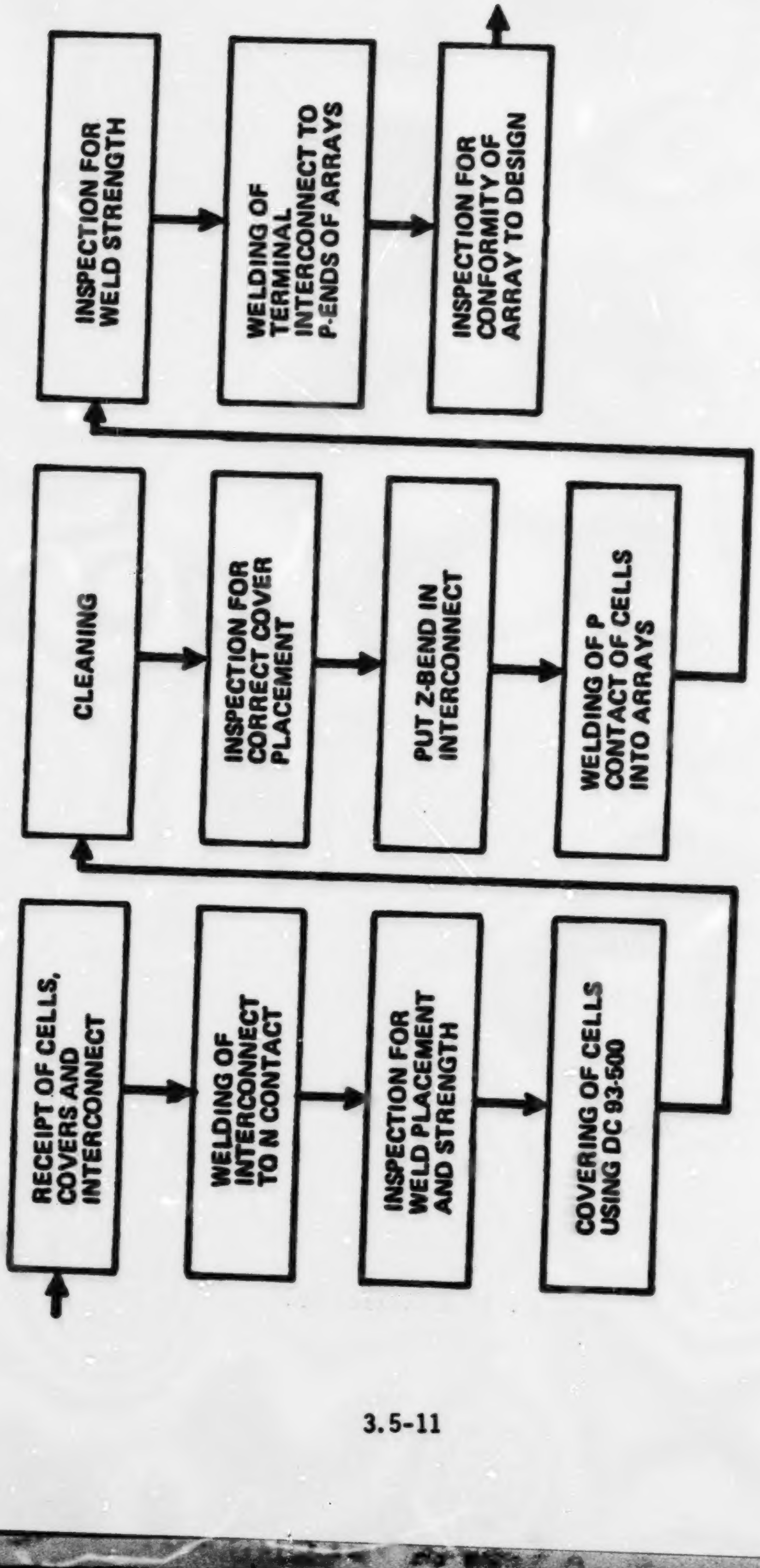

RECEIPT OF CELLS, COVERS AND INTERCONNECT
WELDING OF INTERCONNECT TO N CONTACT
INSPECTION FOR WELD PLACEMENT AND STRENGTH
COVERING OF CELLS USING DC 93-500
CLEANING
INSPECTION FOR CORRECT COVER PLACEMENT
PUT Z-BEND IN INTERCONNECT
WELDING OF P CONTACT OF CELLS INTO ARRAYS
INSPECTION FOR WELD STRENGTH
WELDING OF TERMINAL INTERCONNECT TO P-ENDS OF ARRAYS
INSPECTION FOR CONFORMITY OF ARRAY TO DESIGN

Figure 3.5-3 Assembly Sequence for Cell Strings

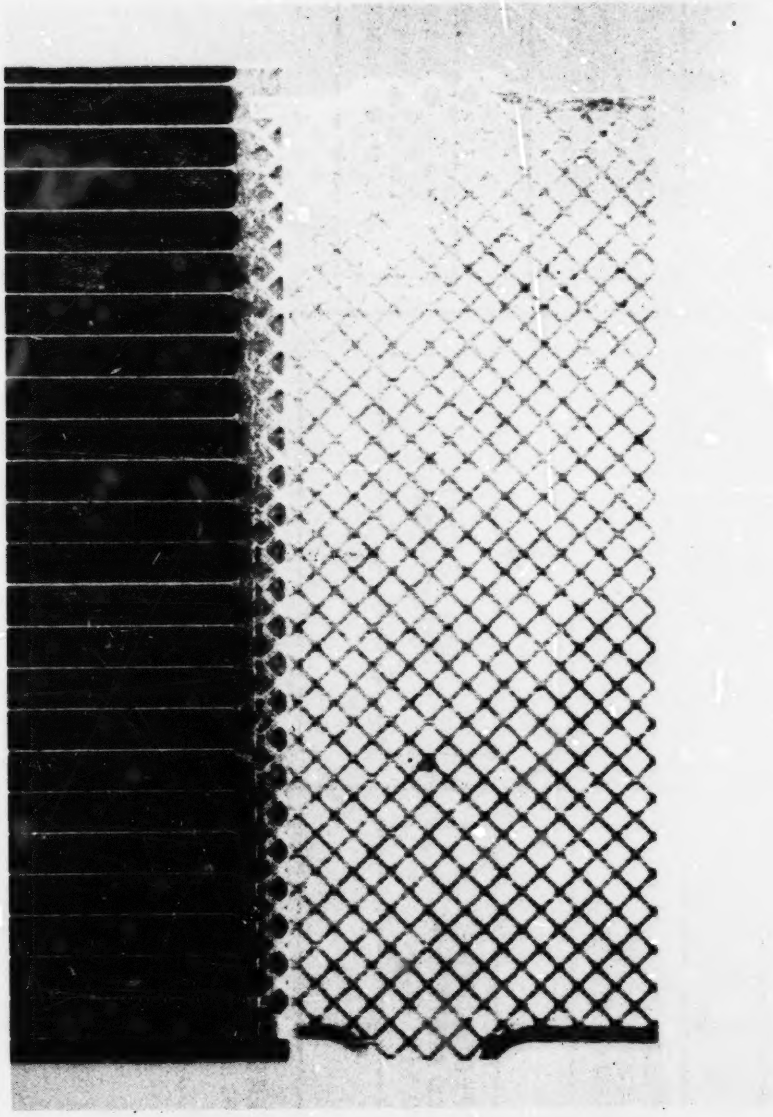


Figure 3.5-4 N Contact Weld

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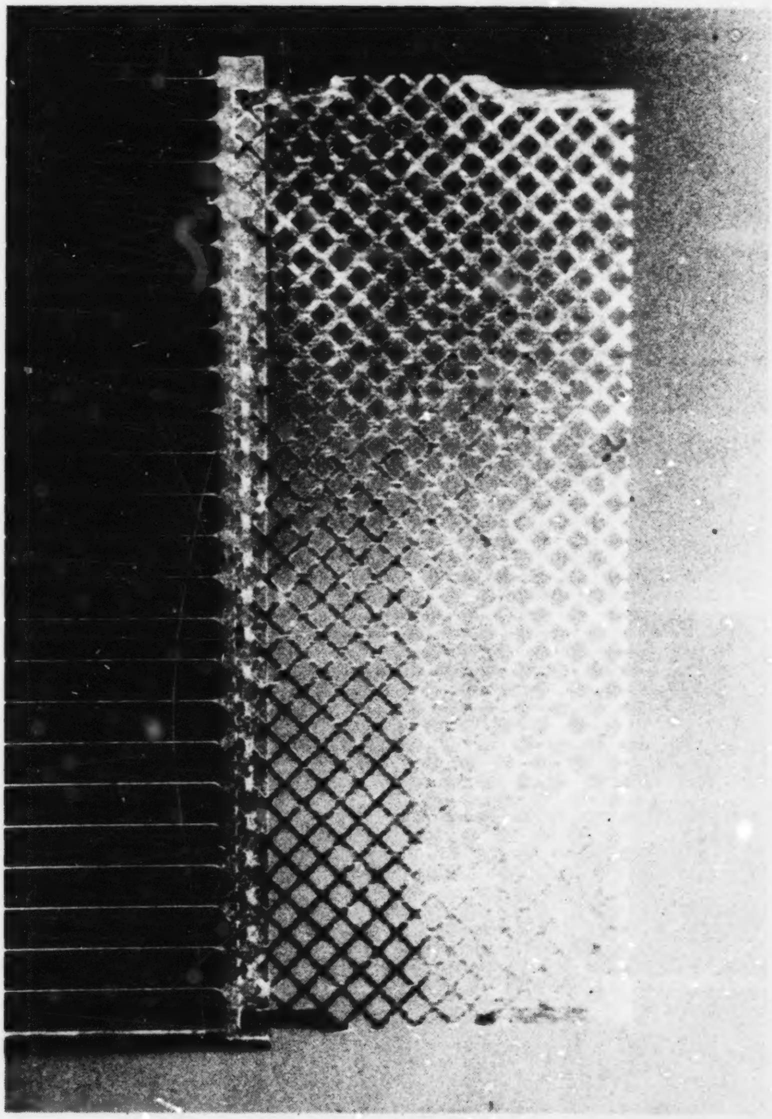

Figure 3.5-5 Duplicated N Contact Weld.

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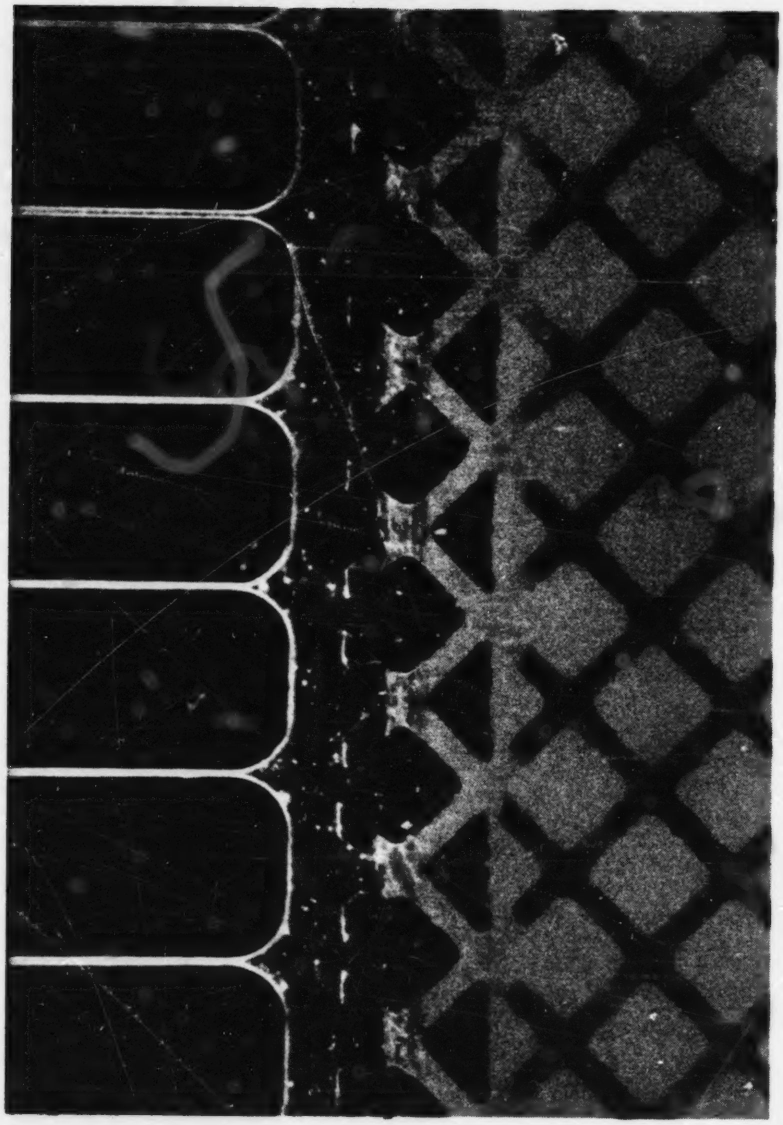
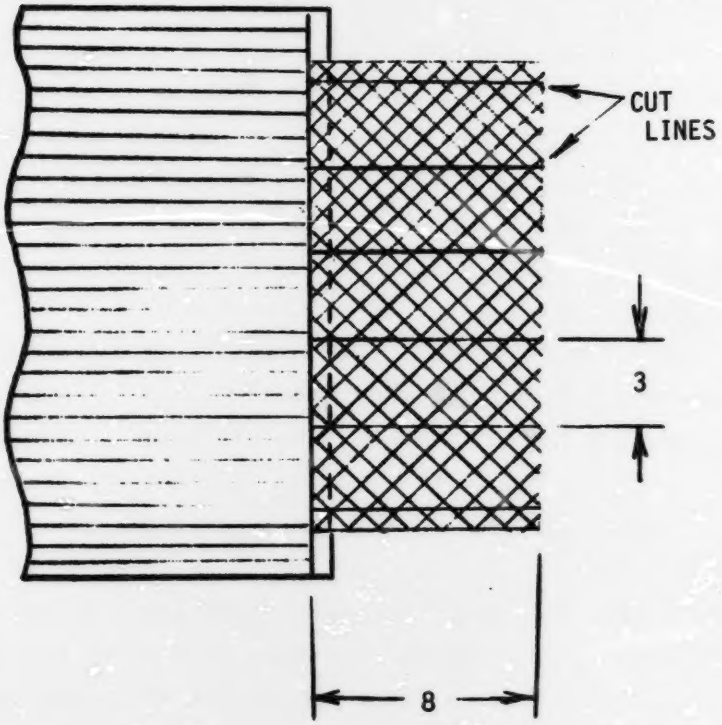


Figure 3.5-6 Welded Mesh Nodes


CUT
LINES
3
8

Dimensions are in millimeters.

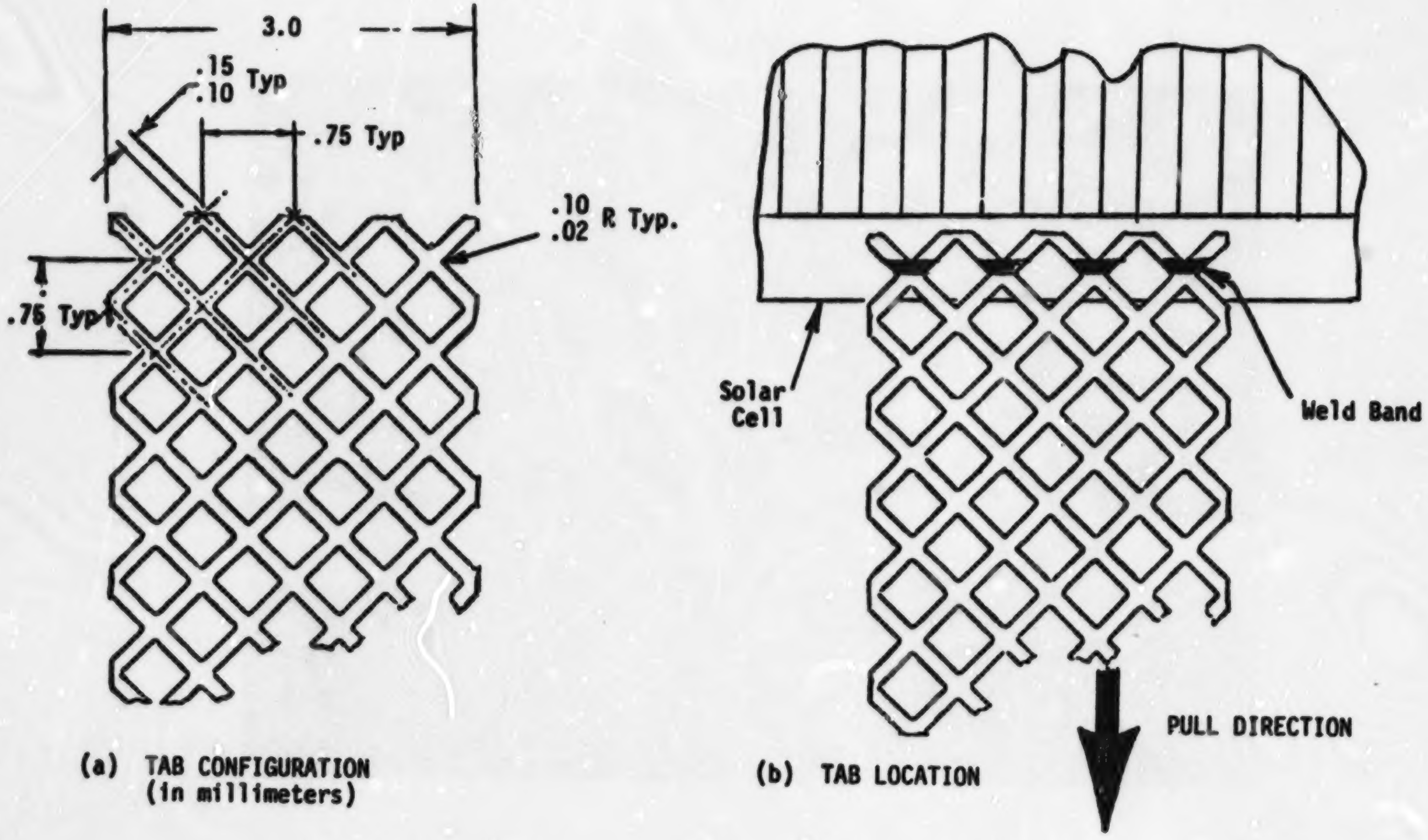
Figure 3.5-7 Formation of Pull Tabs.

The cut was made with an industrial grade razor blade along the row of mesh nodes using a low power microscope to provide visual control of the location of the cut. The result was a series of mesh tabs having the configuration depicted in Figure 3.5-8. This method of welding and then forming tabs ensured that test welds were representative of those used for making cell strings since the welding procedures were identical.

With strong welds, the mesh would distort and rupture before the welds broke. Figure 3.5-9 shows four tabs on an ultrathin cell, all four of which broke without failure of the weld bonds. The force required to distort and rupture a pull tab of the standard configuration (Figure 3.5-8) was between 120 and 200 g, depending upon the width of the individual mesh strands. These strands varied in width from one sheet of interconnects to another as a nominal variation in the chemical etching process used by the supplier to form the mesh from a sheet of solid silver foil. Any pull tab which elongated markedly without rupturing the welds was accepted as evidence that the weld bonds had adequate strength.

Pull tab force tests were made on many cells, covering all the weld variables of the matrix tests summarized in Table 3.5-2. Approximately 450 tabs were individually tested to cover these variables redundantly. Some of these tabs were pulled parallel to the plane of the welds so that the welds were in shear. Others were pulled at a 45 degree angle so that the stress on the welds was a combination of shear and peel. This latter direction of pull was a more severe test than the simple shear pull and provided a degree of discrimination of the weld strengths for welds made under the various conditions.

For welds made with a large force between the wheel and the interconnect, the resultant weld bond was quite strong and could withstand either direction of pull. Figure 3.5-10 is a 0.12 mm thick cell which had all four tabs pulled parallel to the cell surface. Figure 3.5-11 is a similar cell for which the top and the third tabs were pulled at 45 degree while the second and the bottom tab were pull in shear. All welds on both cells survived. As an incidental item in these two photographs, note that the overlap of the mesh on these cells is the same as it is in the previously shown pictures of ultrathin cells. With these thicker cells, however, the N contact bar is only 0.6 mm wide so the mesh extends beyond the bar. The mesh position was kept the same for all types of cells to facilitate including all cells concurrently in each


3.0
.15
.10
Typ
.75 Typ
.10
.02
R Typ.
.75 Typ
Solar Cell
Weld Band
PULL DIRECTION

(a) TAB CONFIGURATION (in millimeters)

(b) TAB LOCATION

Figure 3.5-8 Configuration of Pull Tabs.

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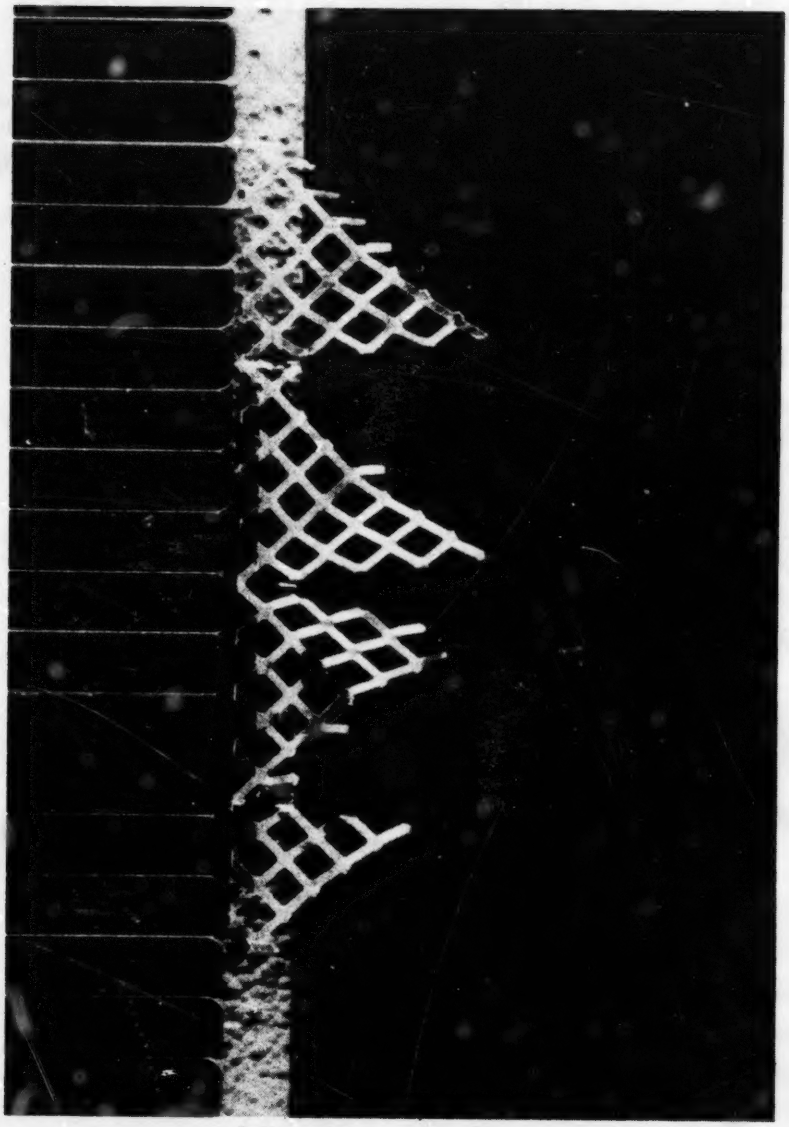

Figure 3.5-9 Weld Tabs on an Ultrathin Cell.

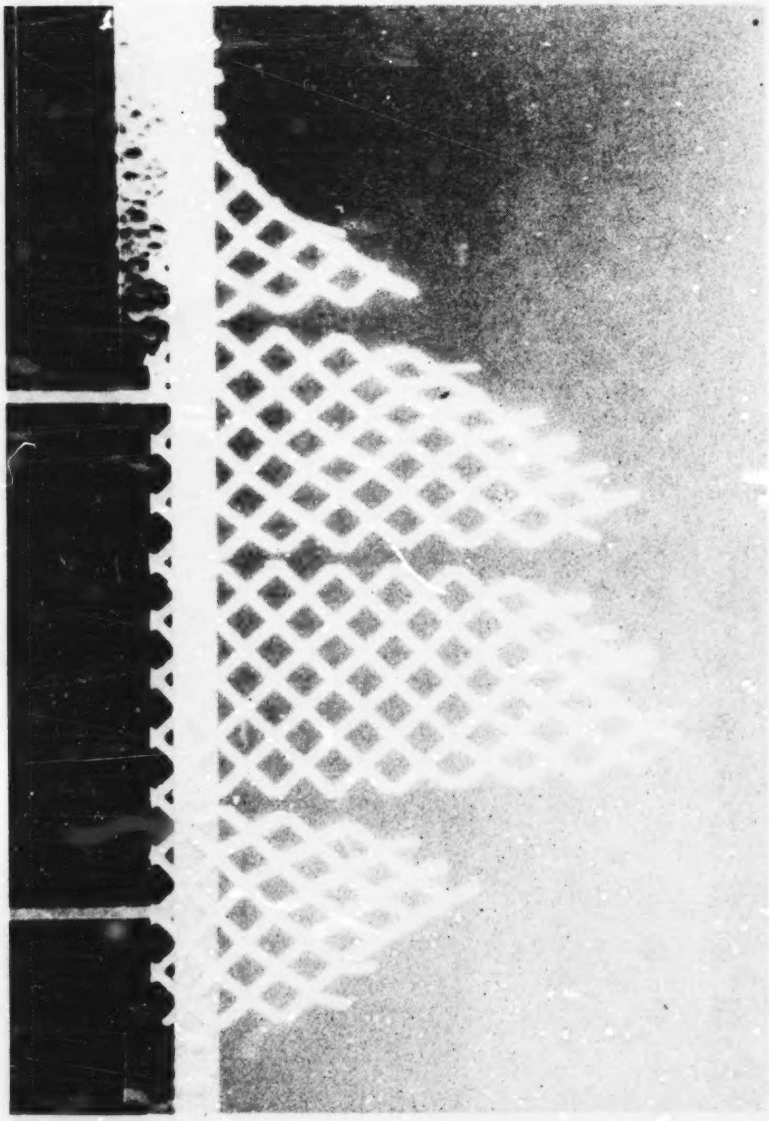

Figure 3.5-10 Weld Tabs Pulled at 0 Degrees

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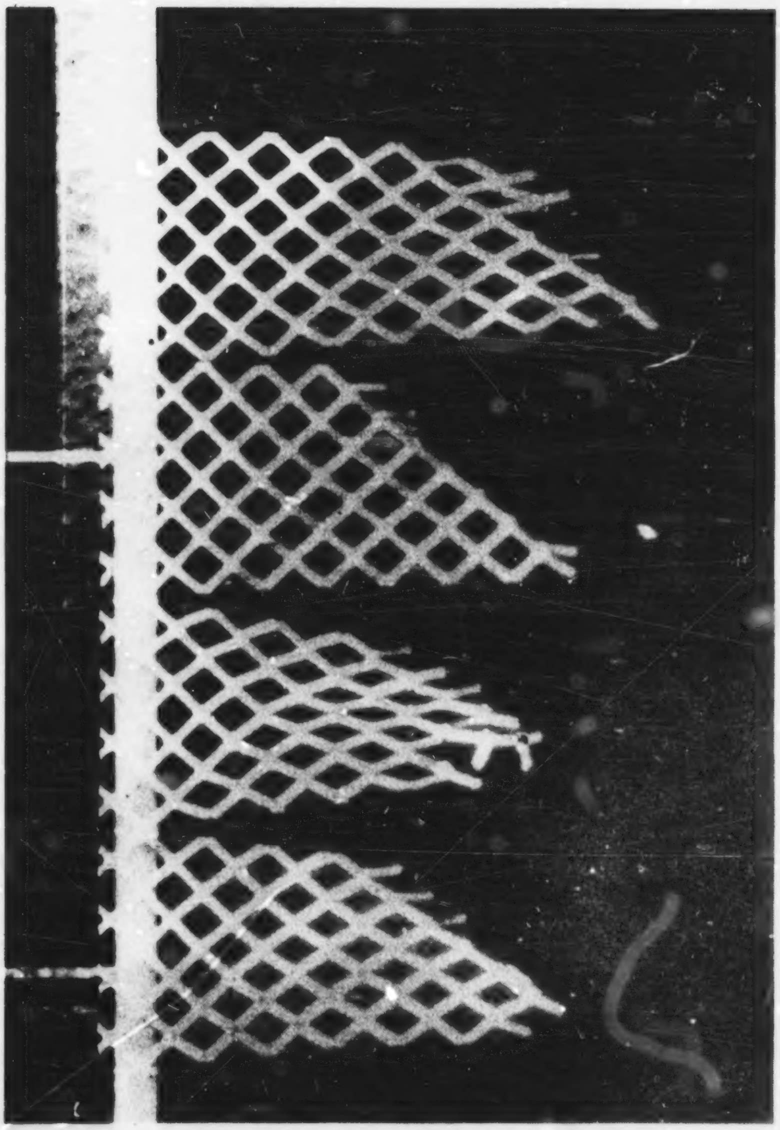

Figure 3.5-11 Strong Welds Pulled at 45 and at 0 Degrees

of the four test matricies. If this had been a production run using only the 0.12 mm thick cell, the machine would have been adjusted so that the mesh would not have extended beyond the edge of its narrow bar contact, thus avoiding the small amount of shadowing that exists with the present overhang.

Figure 3.5-12 shows a set of welds made with a low force between the welding wheel and the interconnect. The top and the third tabs were pulled at 45 degrees. The welds for these tabs failed. The second and the bottom tabs were pulled in shear, and the welds did not fail. Although 45 degree tests could not be run on the ultrathin cells because these cells would break from the resulting bending stress, these combination 45 and 0 degree tests were possible with the thicker cells. From these latter tests it became apparent that values of weld parameters smaller than these used on Matrix IV would not produce welds of adequate strength.

The upper limit on the values of weld parameters that could be used with the ultrathin cells was determined by the desire to avoid cracking of cells during welding. An example of cracks is shown in Figure 3.5-13. They appear to be shear induced cracks arising from the concentrated force placed on the individual mesh strands. Attempts were made unsuccessfully to cause these cracks to propagate after welding was completed. Figure 3.5-14 shows two small cracks (upper weld of center tab) that did not propagate even though the included weld region was pulled in shear hard enough to distort and rupture the adjoining mesh. Figure 3.5-15 shows an area of contact that had been severly fractured during welding. The mesh tab on this area was pull tested with a large force (180 g) so that the mesh distorted before eventually breaking at or near the welds. The stress at the individual weld areas was large enough to cause removal of small divots of silicon, yet the weld induced cracks did not propagate during the tab pull test. Even though electrical performance is not degraded by these weld induced cracks, and we have been unable to get the cracks to propagate with any of the subsequent pull tests, we hesitate to consider that such cracks would be acceptable for flight hardware. Therefore, we would recommend keeping the welding head force small enough to avoid such cracks at the expense of less weld strength.

After interconnects have been satisfactorily bonded to the N contact and inspected, the next operation (see Figure 3.5-3) is to bond a glass cover over the cell. This produces an assembly that is commonly called a covered interconnected cell (CIC). Figure 3.5-16 shows a CIC of an ultrathin cover on an

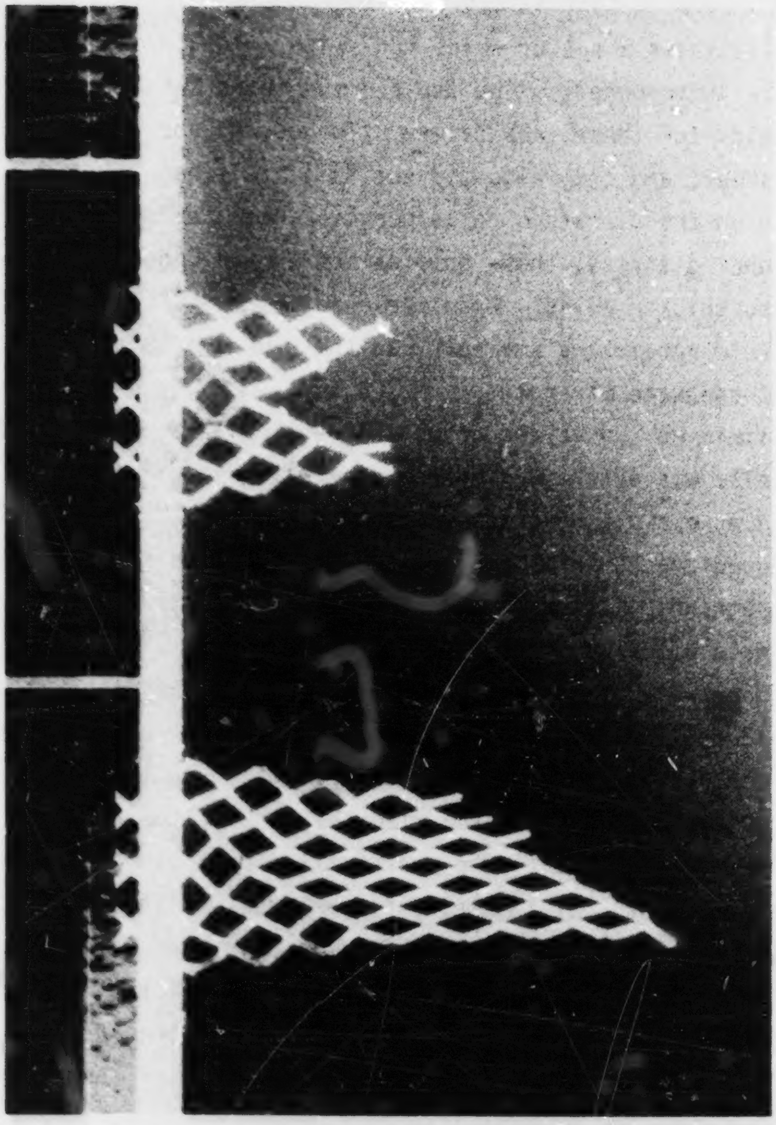

Figure 3.5-12 Marginal Welds
Pulled at 45 and 0 Degrees.

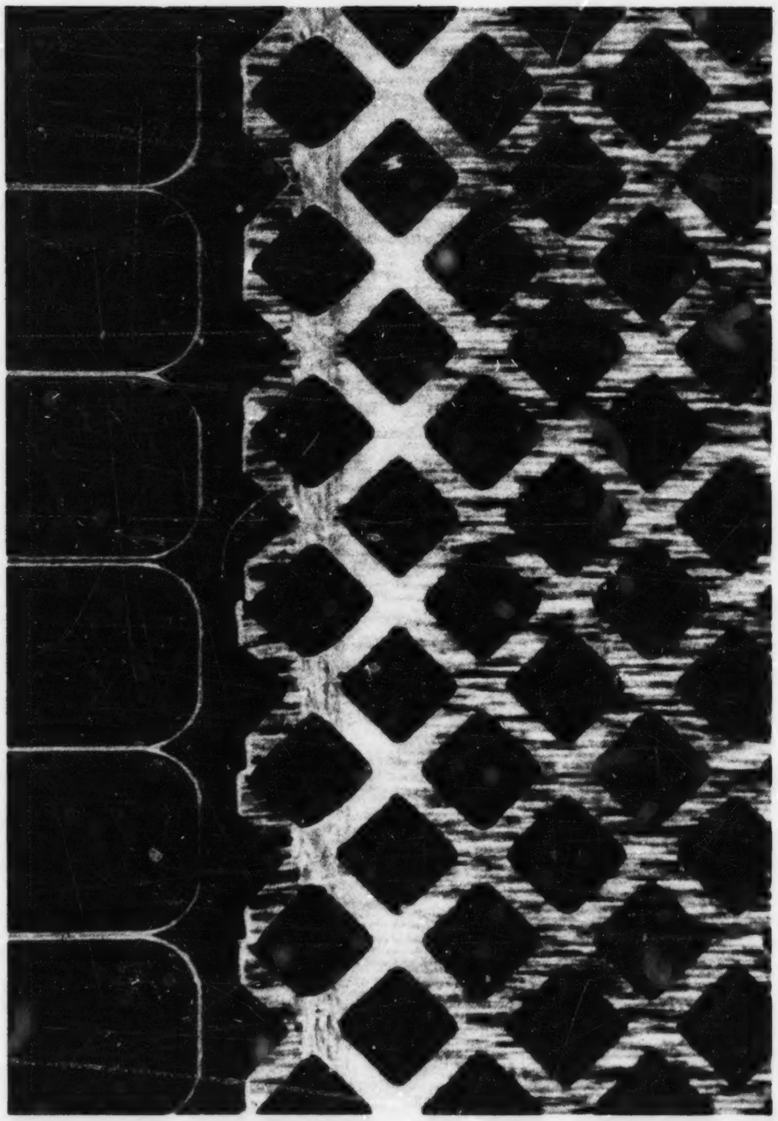

Figure 3.5-13 Cracks in the N Contact

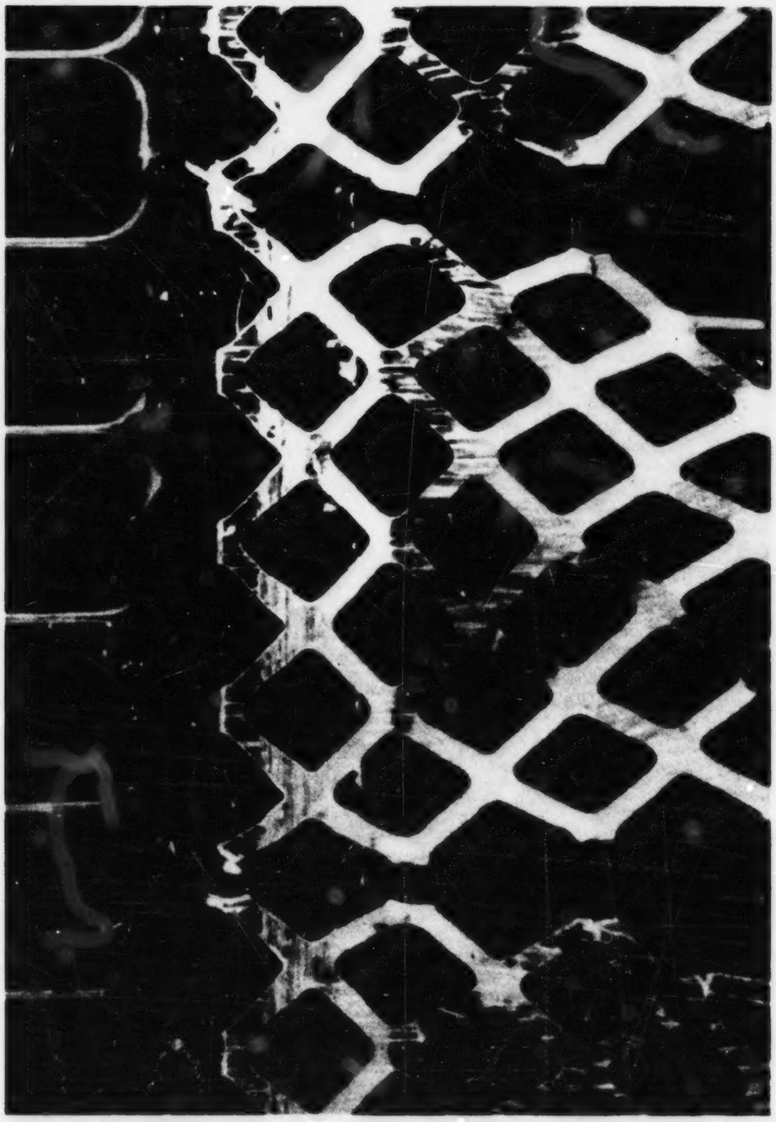

Figure 3.5-14 Nonpropagating Small Cracks

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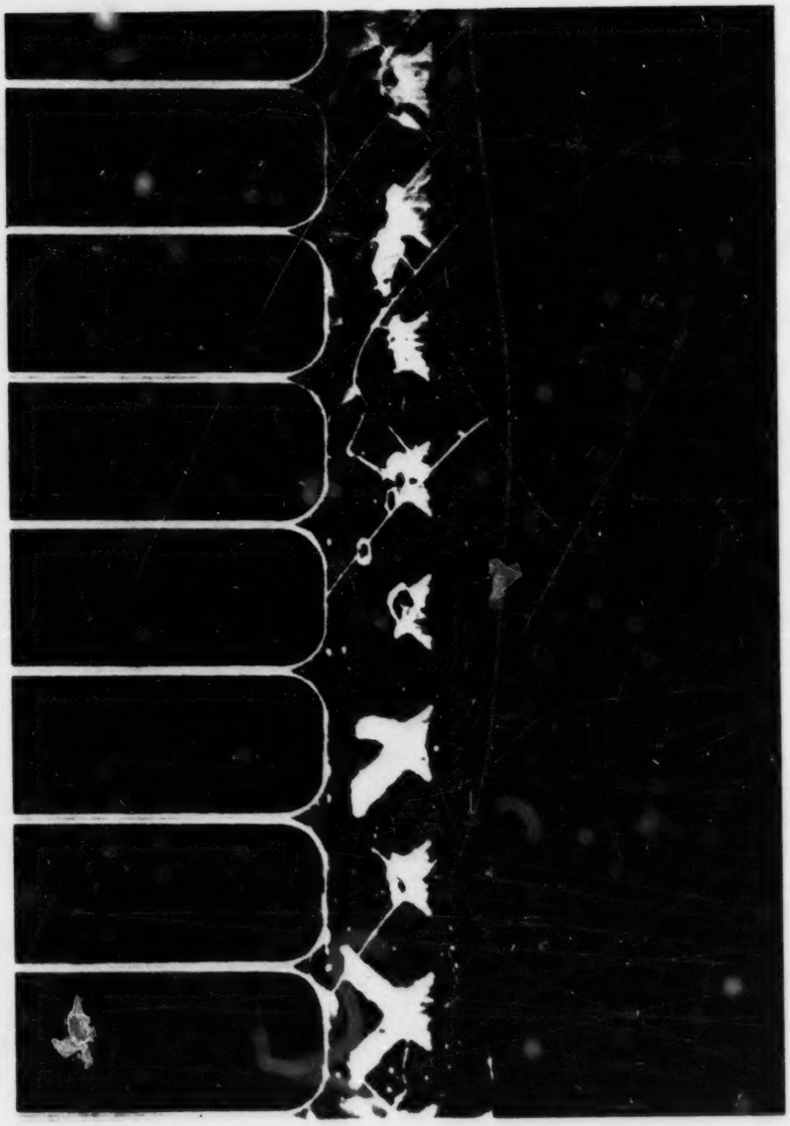


Figure 3.5-15 Nonpropigating Large Cracks.

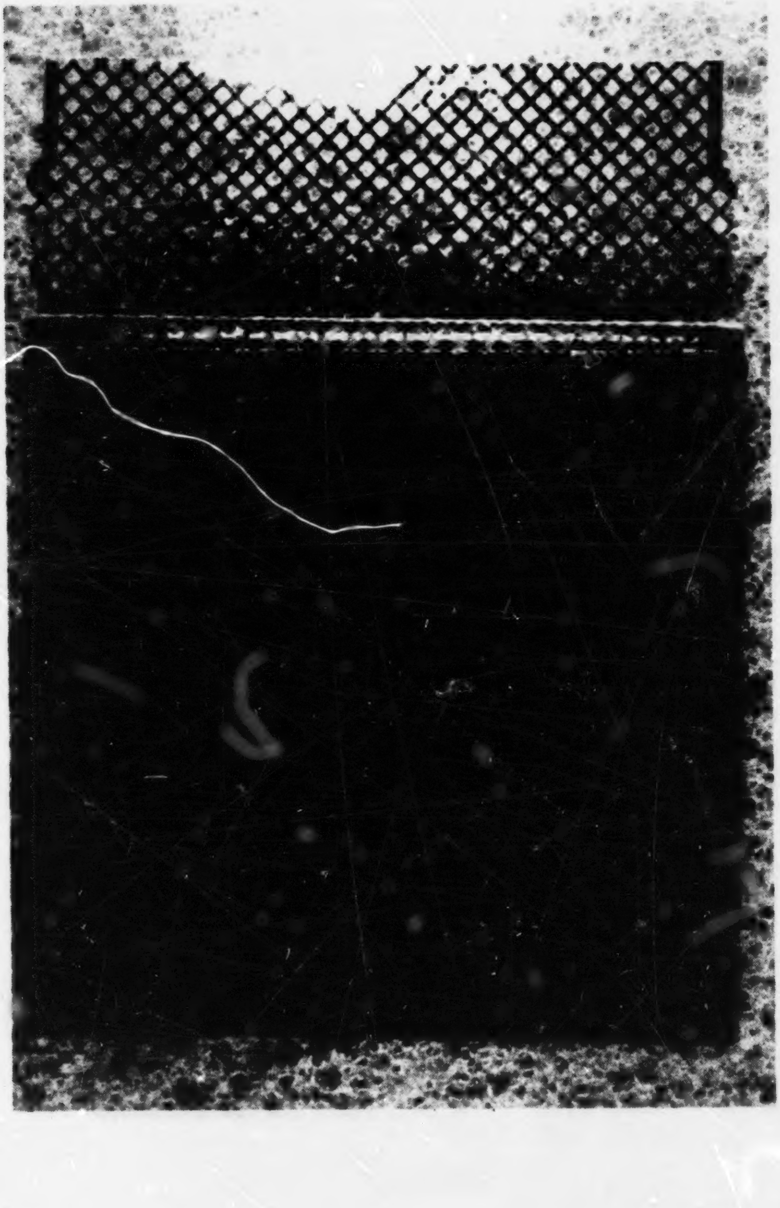


Figure 3.5-16 CIC of Ultrathin Cell.

ultrathin cell. Figure 3.5-17 shows a CIC of an ultrathin cover on a 0.12 mm thick cell. In both cases the glass completely covers the cell, including the N contact and weld area. This complete coverage provides protection from low energy protons, an important consideration when the N contact does not have a protective coating of relatively thick solder. Furthermore, once the contacts are covered with glass, the welds are protected from any subsequent possibility of peeling force. The lower peeling strength of the lightly welded thin cells (per the test result displayed in Figure 3.5-12) then is no longer a potential hazard.

The formation of series cell strings is a relatively simple matter of welding the extended edge of the front welded interconnect of one cell to the back of the adjacent cell as indicated in Figure 3.2-7. Figure 3.5-18 shows the front side of 4 series strings composed of the 4 types of cells used in this project. Figure 3.5-19 shows the back side of these 4 series strings. The strings in Figure 3.5-18 have been fabricated from uncovered cells rather than from CIC's to investigate whether these shallow diffused cells would suffer any electrical loss when they must rest with their shallow diffused front junctions so close to the support anvil while undergoing an ultrasonic agitation. No electrical damage was detected. With the ultrathin cells, however, a visual effect was noted; the grid lines immediately under the weld line gained an added reflectance. This can be observed in Figure 3.5-18 on the lower portion of each of the ultrathin cells. It is also apparent in the enlarged view of Figure 3.5-20. Under further magnification this is seen in Figure 3.5-21 as a slight flattening of the gridlines where the ultrasonic energy has caused the grid lines to be slightly peened by the supporting anvil. This is merely a cosmetic effect with no detriment to the operation of the cells. This flattening does not show up on thicker cells, an example of which is in Figure 3.5-22. A different type of visually apparent artifact is common in photographs of backs of cells in Figure 3.5-19. These are scratches left by the water cooled fixture which held the cells while their photovoltaic response was being measured under Air Mass Zero illumination.

The welded backs of the four different types of solar cells are shown in Figures 3.5-23 through 3.5-26. All were easy to weld. Besides the scratches apparent on the backs of all cells (as noted in the preceeding paragraph), the two cells of intermediate thickness with the smooth, boron doped P^+ back

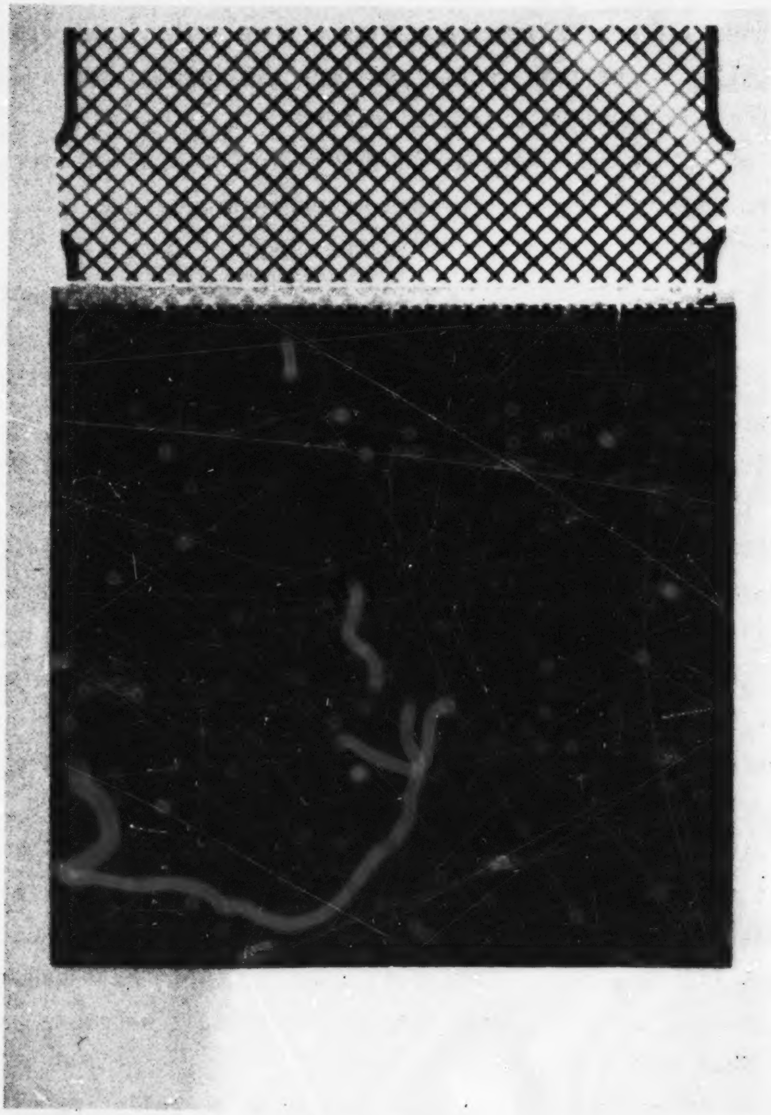
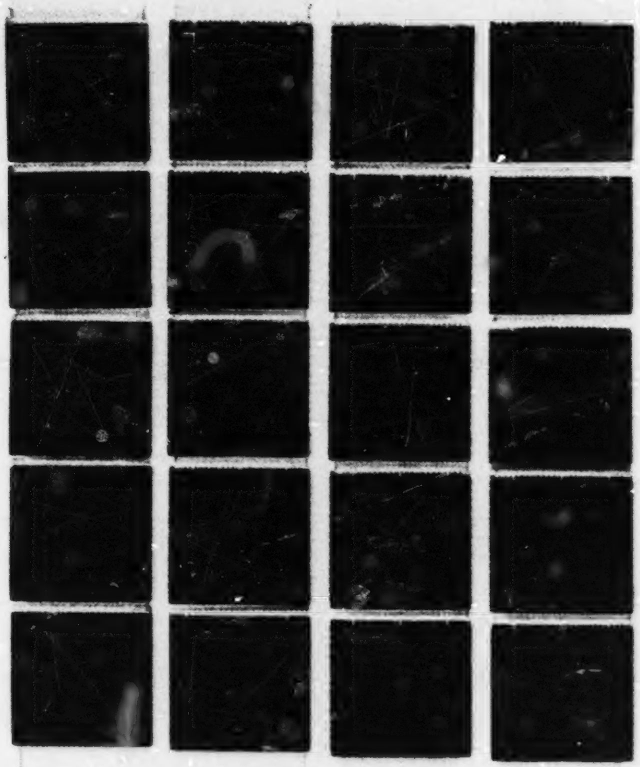


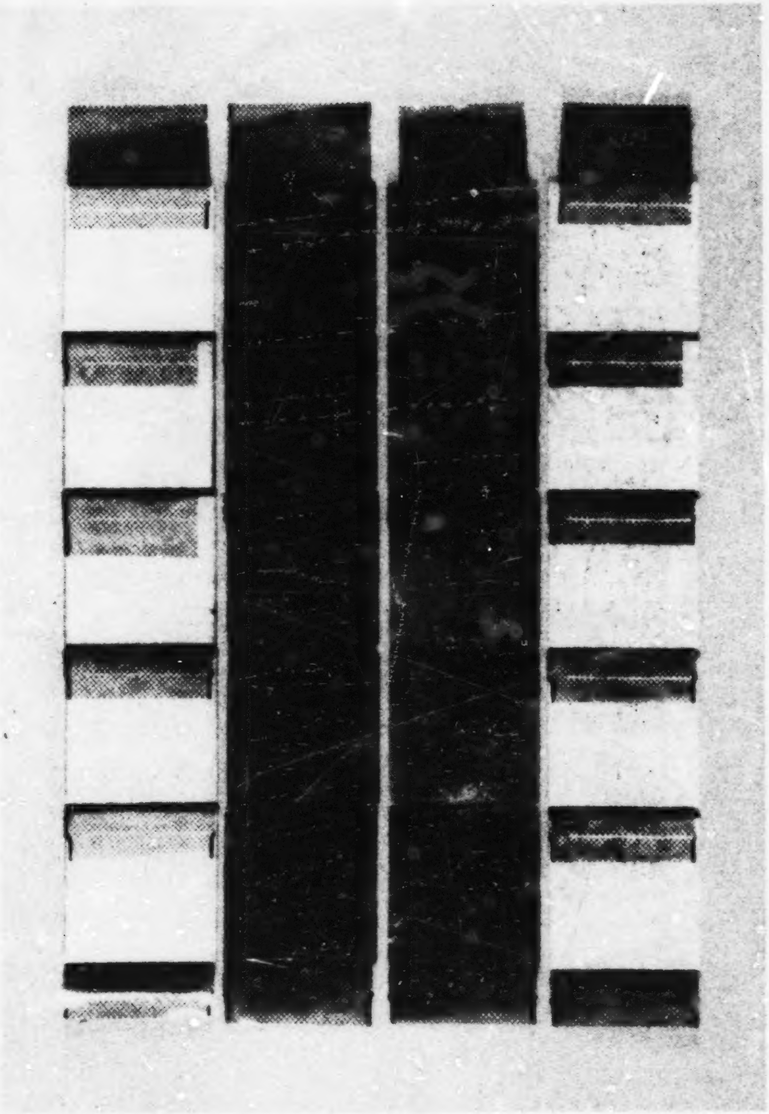
Figure 3.5-17 CIC of 0.12 mm Thick Cell.



Type A Type B Type C Type D

(refer to Table 3.3-1 for cell descriptions)

Figure 3.5-18 Series Strings (Front Side)



Type A Type B Type C Type D

(refer to Table 3.3-1 for cell descriptions)

Figure 3.5-19 Series Strings (Back Side)

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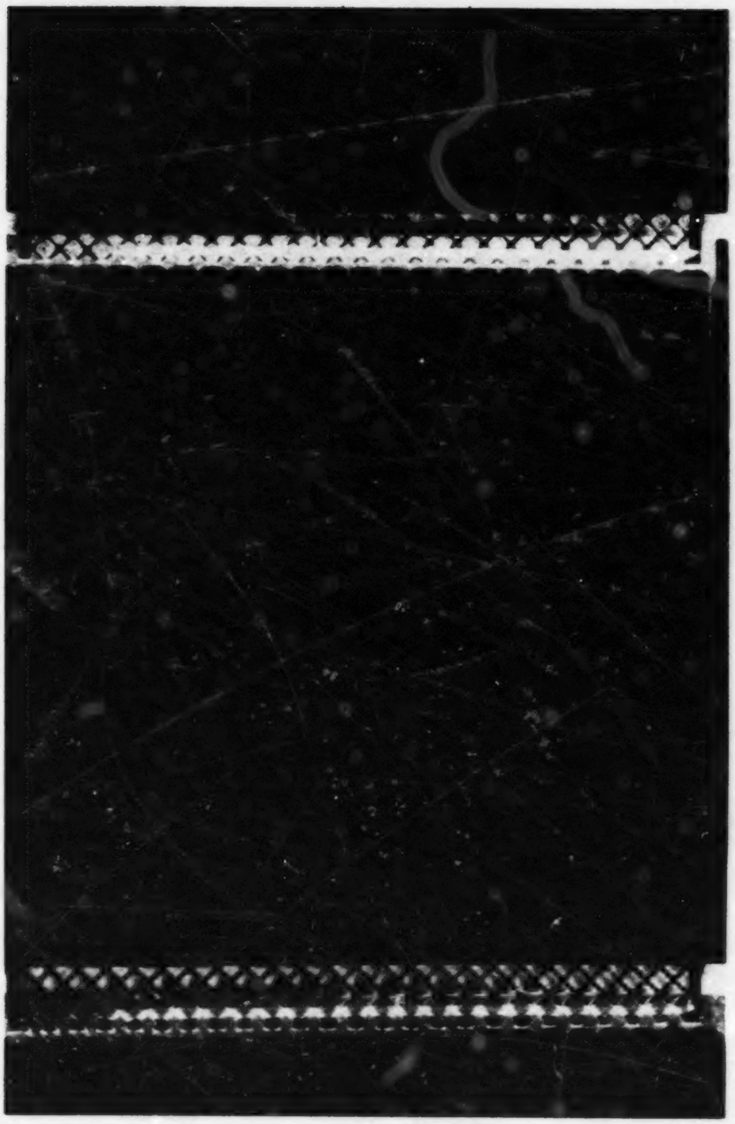

Figure 3.5-20 Front of an Ultrathin Cell in a Series String.

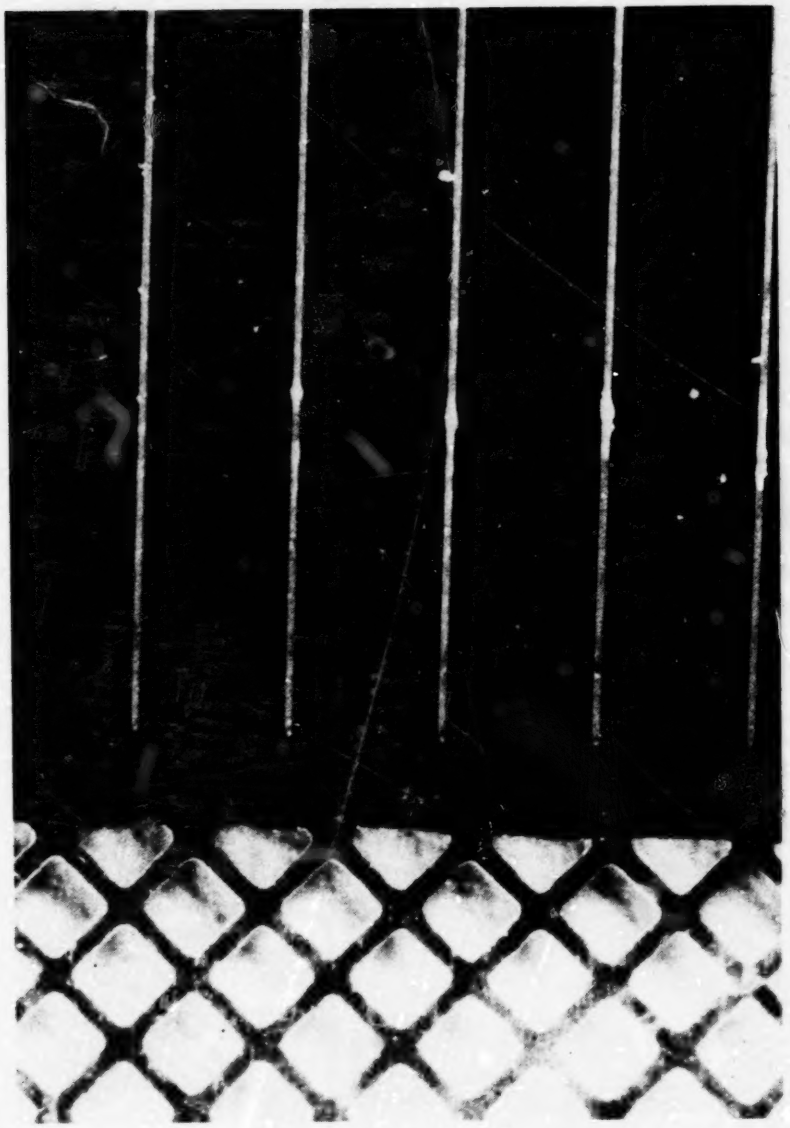

Figure 3.5-21 Flattened Gridlines

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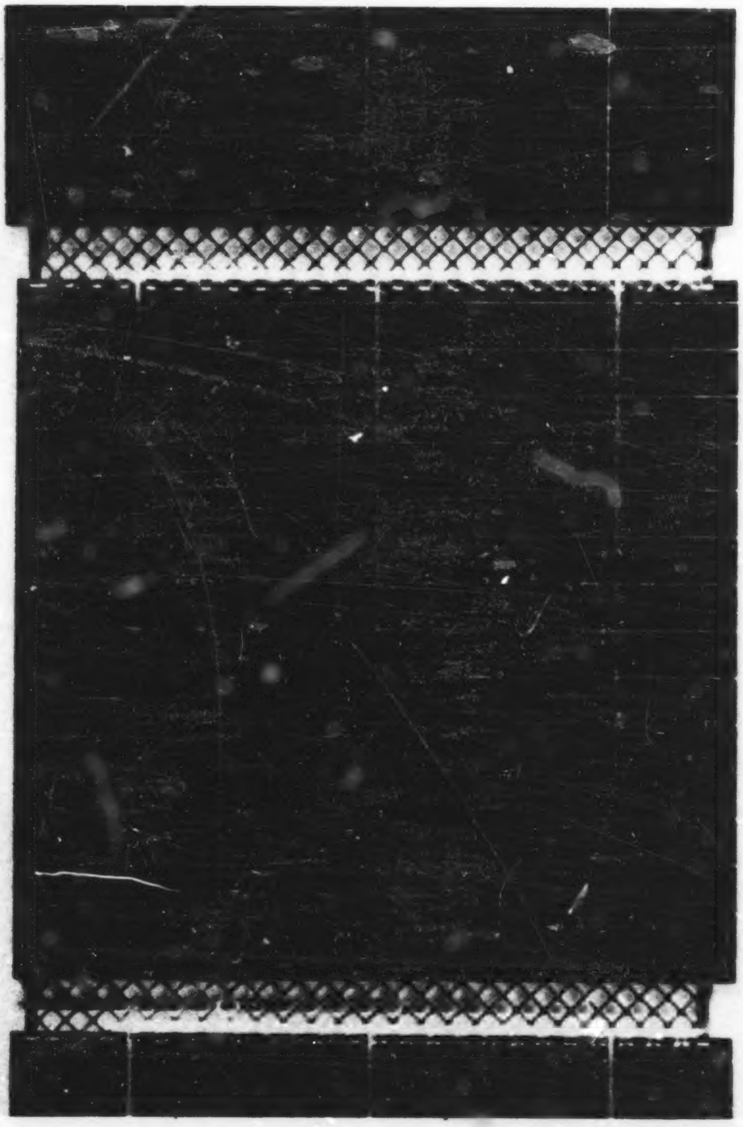

Figure 3.5-22 Front of 0.12 mm Thick Cell in a Series String.

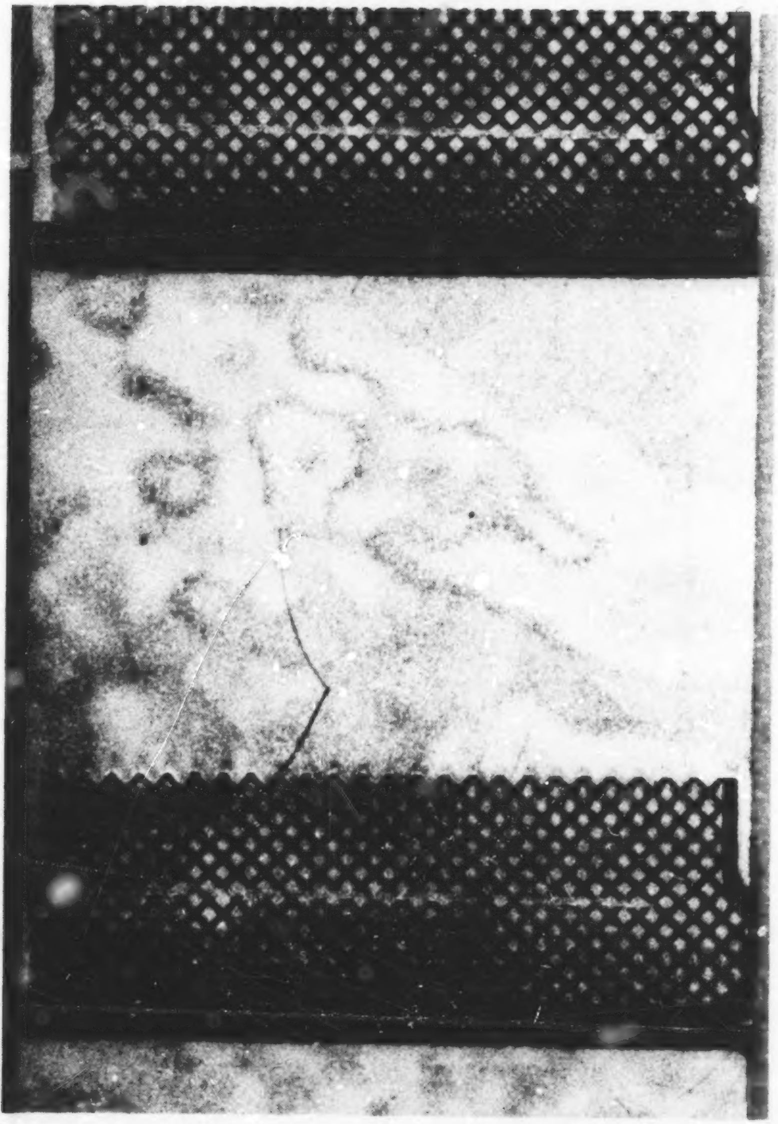

Figure 3.5-23 Back Weld on Ultrathin Cell

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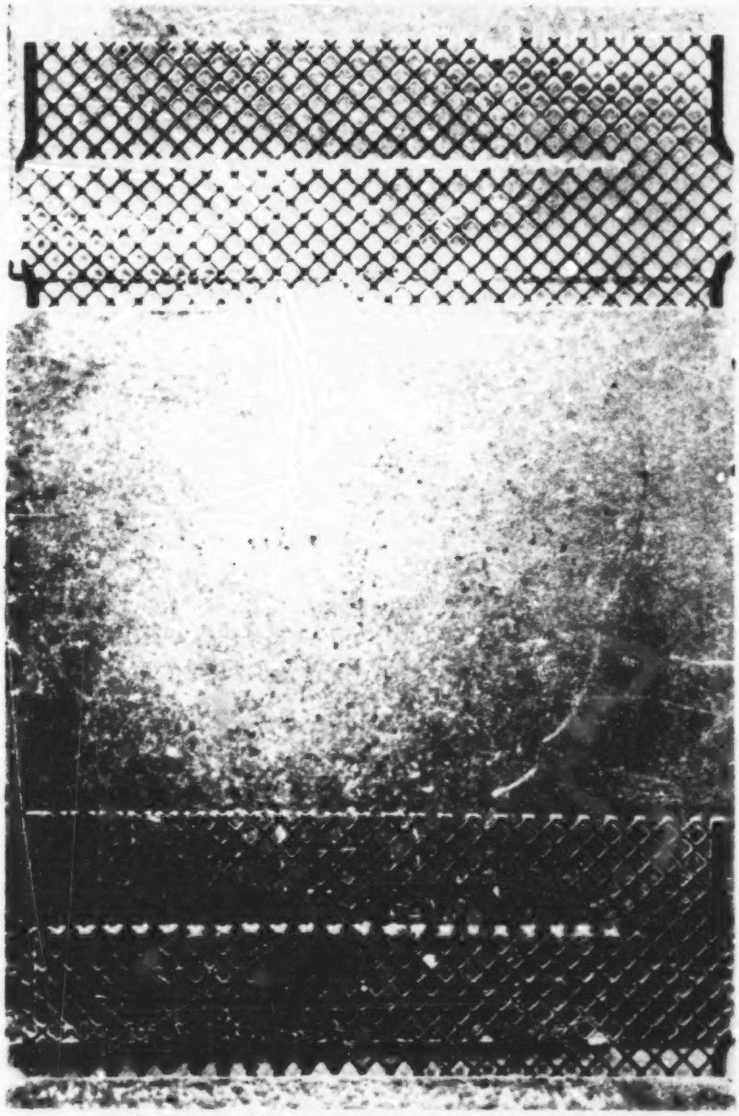

Figure 3.5-24 Back Weld on 0.12 mm Thick Cell

Figure 3.5-25 Back Weld on 0.16 mm Thick Cell

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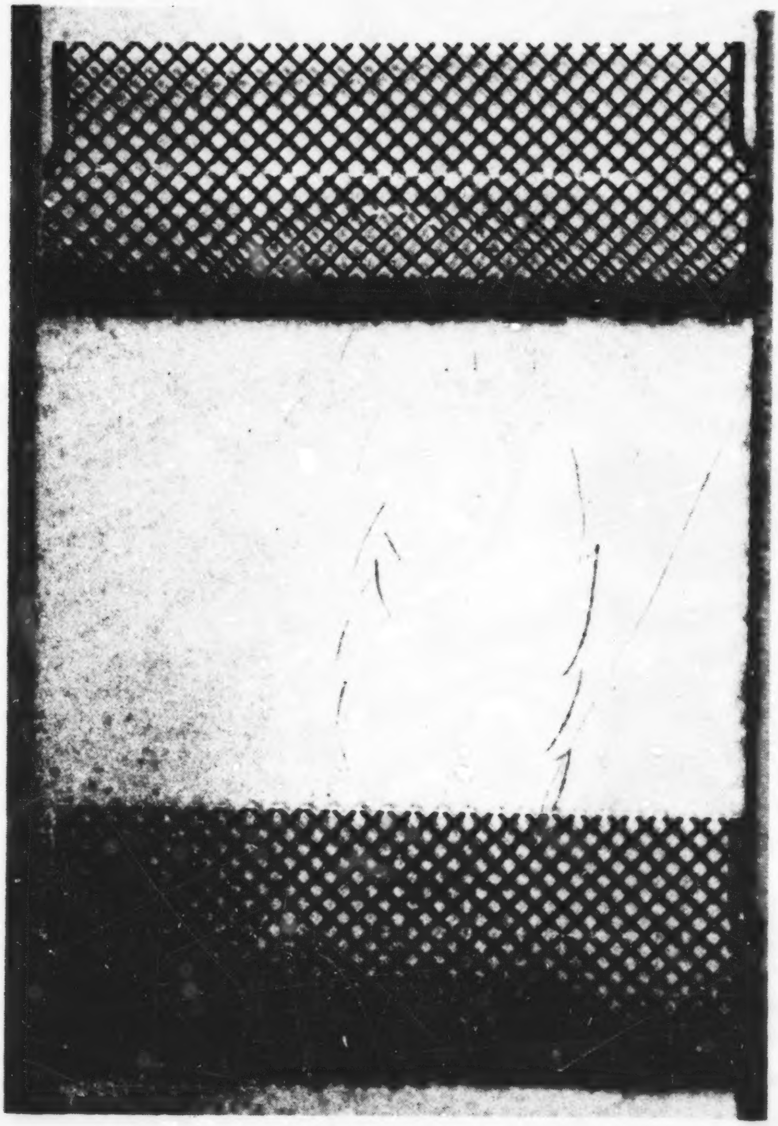

Figure 3.5-26 Back Weld on 0.21 mm Thick Cell

contact had evidence of slight peening of this contact surface as a result of the welding that had been performed on the front surface. This peening is the light toned region along the upper edges of these two cells. This caused no degradation in cell performance. Close-up views of typical rear welds on cells are shown in Figures 3.5-27 and 3.5-28. Figure 3.5-29 shows a weld where the welding wheel was allowed to go beyond the edge of the mesh on an ultrathin cell. The only effect was to scuff the back contact. The cell did not crack nor was there any degradation in electrical properties.

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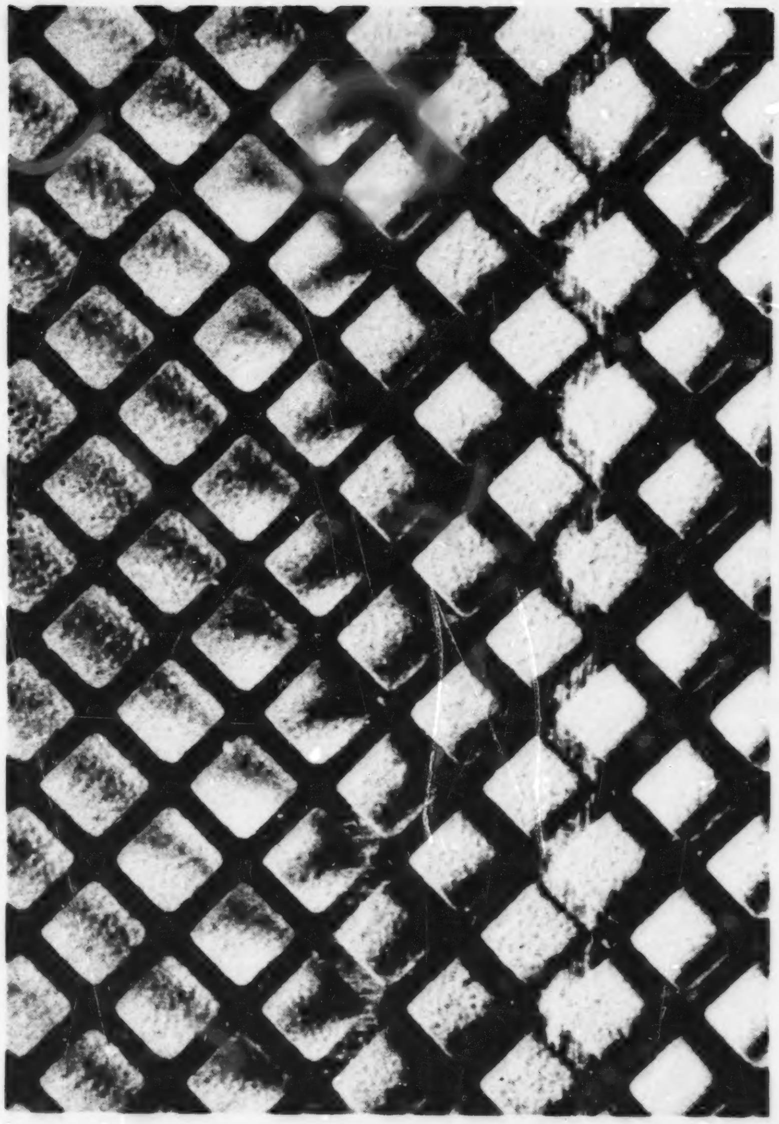

Figure 3.5-27 Close-up of Welded Back of Ultrathin Cell.

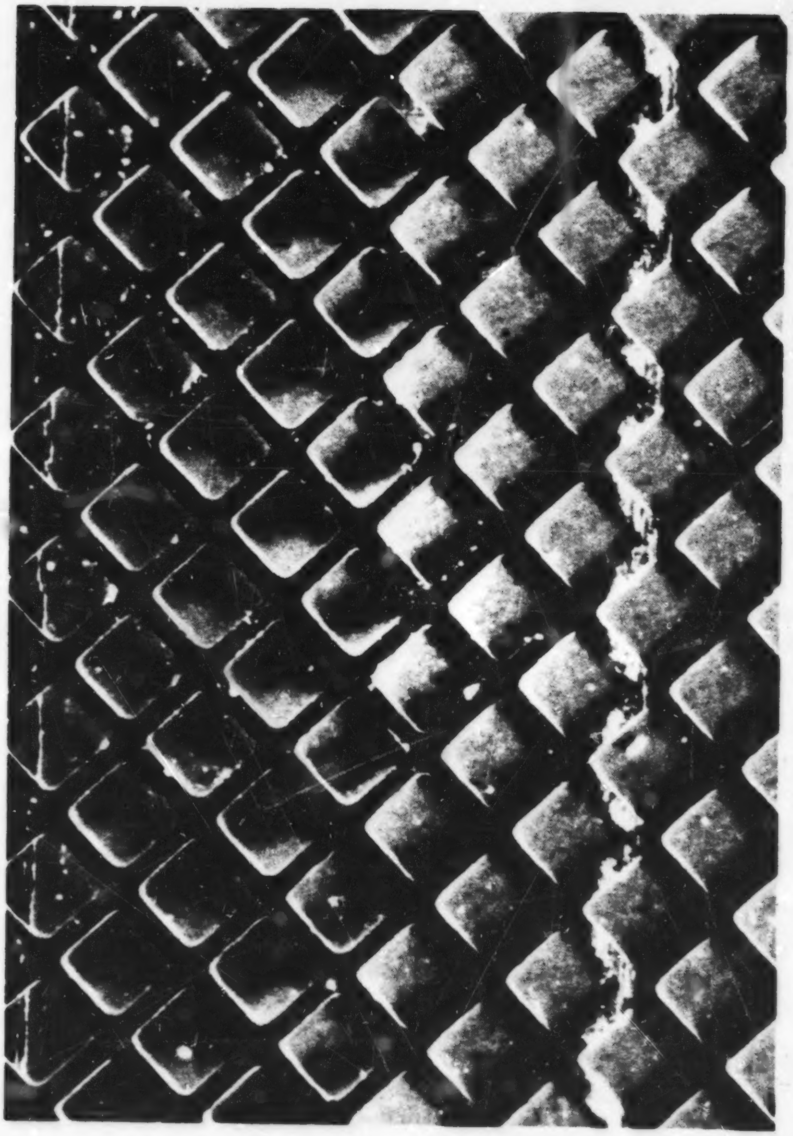

Figure 3.5-28 Close-up of Welded Back of 0.12 mm Cell.

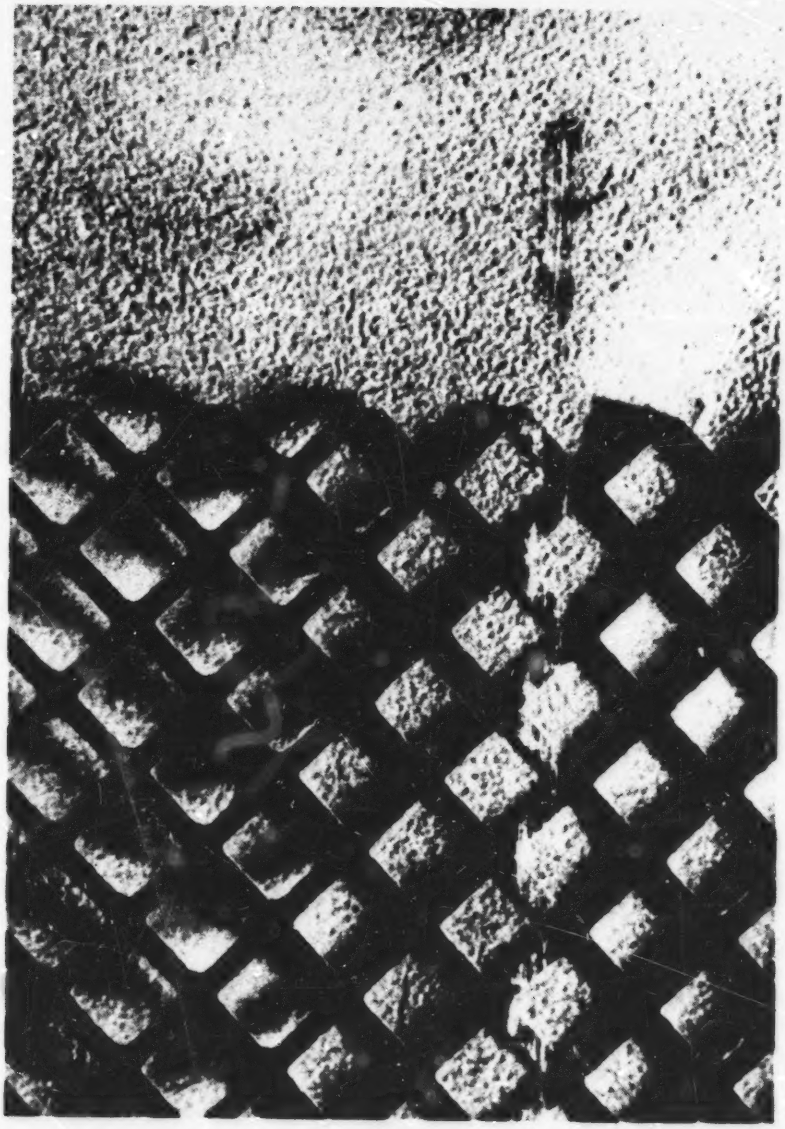

Figure 3.5-29 Close-up of Back Weld Scuff Mark.

3.6 COVERING

While the major emphasis of this project has been on determining the optimum means of welding interconnects to ultrathin silicon solar cells, a small part of the effort also was directed toward bonding ultrathin glass covers to these cells. The covers fabricated by OCLI and supplied to this project by JPL, were 0.050 mm thick with a rough etched surface. They were formed of Corning 7940 fused silica and were without coatings. Handling these pieces of glass with plastic tweezers or vacuum pencils proved no more difficult than handling the ultrathin solar cells. After a little practice, handling could be accomplished without breakage.

These covers were applied to solar cells using Dow Corning 93-500 clear silicone adhesive in a manner similar to that used for thicker glass. A drop of the freshly mixed DC 93-500 and hardener was placed on a cover, and the cover then placed over the front side of the solar cell. A simple alignment fixture, consisting of a few pins at the edges of the cover and cell acting in concert with a small weight used to press the cover close to the cell, was used to maintain the cover in proper location over the cell during the curing period of the adhesive.

Only two problems were encountered in bonding the ultrathin covers to the ultrathin cells: accomodating the slight curvature that was typical of the ultrathin solar cells, and removing the excess adhesive from the completed cover to cell laminate after the adhesive was cured. The curvature of the ultrathin cells has been described in section 3.5.1 of this report. The ultrathin covers were not curved. When the covers were placed on the cells using the alignment fixtures available for this program, the convex curvature of the front of the cells tended to remain. Thus, the cured adhesive was thicker at the edges of the cells than at the center. Undoubtedly, a modified alignment fixture that would place a greater force between cover and cell so as to press the cell flat against a supporting anvil during the period of adhesive cure would eliminate this effect in the future. For the present project, however, this curvature effect was not deemed important enough to warrant modifying the alignment fixture at this time. The slight curvature remaining in the covered cells did not have an adverse effect on subsequent welding of interconnects to the backs of covered cells.

The other problem with the covering process, that of cleaning up adhesive after the adhesive was cured, was more difficult. In applying the freshly mixed, still liquid DC 93-500 silicone to the covers, it is important that the quantity be sufficiently large to eventually spread to the edges of the cover. Unless the adhesive fully fills the space between cover and cell, the edge of the ultrathin cover will be unsupported and thereby be more susceptible to breakage. In covering production quantities of cells, it would be difficult to maintain close tolerance on the amount of adhesive applied to each. Therefore, in order to assure a supply of adhesive sufficient to reach the edges of the cover, it is necessary to add a slight excess of adhesive. This is done commonly today on mass covering of cells for present flight arrays. The excess liquid adhesive is extruded beyond the edges of the cover and is removed after it hardens. For today's typical flight type covers which are thick, have a smooth surface, and are coated with magnesium fluoride, this cleaning of the excess cured adhesive from the edges and face of the covers is only a minor problem. The cured adhesive does not bond well to the smooth magnesium fluoride surface and so can be removed by relatively light rubbing of the surface. For the rough, uncoated ultrathin covers, however, the adhesive bonds strongly to the clean silica surface. A large force is required to remove the cured adhesive, a force so large that the relatively fragile edges of the ultrathin cover break.

Since the significant problem with the ultrathin covers was that they had been received with no coating on the glass that would serve as a low adhesion parting surface, we looked for a material that we could apply easily to one side and thereby serve as this parting agent. After trying several materials, a simple coating of commercially available fingernail polish proved to be practical. It was easy to apply to one side of the cover without contaminating the other side. Since it was brightly colored it was simple to inspect for coverage. Once dried the coating did not smear. The DC-93-500 did not stick to the coating. The coating was easily removed with methyethylketone (MEK) without leaving a residue. While the hand application of this material to covers was too tedious to consider for future mass handling of flight quantities of covers, it was no problem for the few covers needed for the present program. For future flight covers, an outer coating of magnesium fluoride or other material would be appropriate.

4. CONCLUSIONS

This project has demonstrated that ultrasonic welding is a viable method for attaching interconnects to ultrathin cells. Using a prototype ultrasonic machine that has been design specifically for welding interconnects to solar cells, welds were made on ultrathin cells in a reproducible manner. This reproducibility is excellent, suitable for producing space quality solar arrays. This machine has been modified to handle the ultrathin cells, without breakage, at a welding speed sufficient to support production rates practical for fabricating large arrays.

The welding of interconnects to ultrathin solar cells requires closer tolerance on welding parameters than does the welding of thick cells. Control of welding clamp force and weld head ultrasonic energy is especially important. This project has demonstrated that the prototype machine can easily maintain the required precision. The need for this precision is due to the fragility of the ultrathin cells, If the applied force or ultrasonic energy is too large, small cracks are formed near the welds. If the force or energy is too small, the resultant weld bond is mechanically weak. With conventional, thick cells the lower limit restriction is similar; however, the acceptable upper limit is much higher.

While the welding machine variables were investigated in detail to demonstrate that adequate machine control is present, the control of the tolerance on specific solar cell contact configuration variables may be equally important. The cells used in this project all had evaporated silver contacts 0.003 to 0.007 mm thick. Both ASEC and Spectrolab cells were included. The back contacts were all of the P^+ type. Two of the four types of cells studied had this P^+ formed with the aluminum paste process; the other two types had the P^+ formed with boron. The paste process cells had rough back contact surfaces; the boron process cells had smooth back surfaces. Within this range of variables, typical of production runs made with current cell manufacturing technology, welds were adequate. No cells were available with a thicker or thinner silver layer that would provide an indication as to whether silver thickness could be optimized specifically for ultrasonic welding. Some cells in this project were intentionally abraded just before welding to provide a slight increase in surface roughness.

Welds made to such roughened surfaces appeared to be slightly stronger. The detailed study of the optimum degree of roughness and of the best method for introducing such roughness on the contacts would be a major undertaking by itself and therefore was not part of the present project.

All interconnects used in this project were formed of 0.025 mm thick silver, chemically etched to suitable shape. The shape used for most welding was a simple diamond patterned mesh. This has been used previously by Hughes for welding on thick cells. Satisfactory welds were achieved also on the ultrathin cells of this project. Depending upon the type of array substrate to be used and upon the severity of thermal cycling, the interconnect of the future could be entirely of this mesh configuration or else have the central section formed into the S-shaped, high compliance configuration now used on many Hughes spacecraft.

Cells were covered with ultrathin silica covers using clear silicone adhesive. These covered cells, as well as uncovered cells, were welded together to make series connected cell strings. No serious difficulty was encountered in forming these cell strings.

5. RECOMMENDATIONS

The work of this project supports the feasibility of using ultrathin solar cells for space application. Therefore, continued development of these cells should be encouraged. Specific recommendations are:

- Continue developing for thin cells a manufacturing production capability large enough to support spacecraft quantities.
- Investigate cell contact thickness and surface finish as variables to be optimized for welding.
- Investigate the relative merits of interconnects of solid silver compared with silver plated Invar or other materials.
- Perform long term thermal cycle endurance tests to demonstrate fatigue limits of welds.
- Develop non-destructive methods for determining the soundness of welds, including methods that can be used for routine on-array inspection.
- Develop methods for repairing damaged solar arrays that can be used any time before launch.

6. NEW TECHNOLOGY

This report does not contain items of new technology development by Hughes Aircraft Company under this contract.